Comparing the performance of technological innovations operating at different scales to improve the circulation of biogenic household waste flows

The case of Amsterdam

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PREFACE AND ACKNOWLEDGEMENTS

I strongly believe that nature can serve as an inspiration to find solutions to many of the challenges the humankind is facing nowadays. During my Bachelor's, I was fascinated by the extremely smart functioning of living organisms, from the human cell physiology to the perfect geometry of a bee hive. Not surprising if one takes in consideration the countless centuries of optimisation that evolution has posed in living systems. Later in one of my Master's course, I had the chance to work in a case study about Biomimicry, a discipline consisting in learning from nature to inspire design. During that course I became very interested in the idea of applying the principles of natural systems in human systems, specially cities. Cities concentrate intensive human activities causing severe environmental pressures and it is therefore urgent to improve its sustainability. After some weeks of reading to get some inspiration for this thesis, I came across the Circular Economy model, which aims at designing sustainable production systems by cycling materials into infinite material loops as happens in natural ecosystems. I was fascinated by this idea and thus, I decided to focus my thesis in studying the application of Circular Economy in cities.

Thus, the ideation and proposal writing of this thesis took quite a long time. The progress of it was also challenging because Circular Economy is generating a lot of momentum, but it is quite recent discipline that is still maturing and developing its own methods.

Firstly, I would like to thank my supervisor Dr. Karen Fortuin for helping me grounding and getting my broad range of interests narrowed down into a researchable idea. I also want to thank her for all the sharp feedback she has provided me with, which has added a lot of value and improved my findings. I want to thank Dr. Wim the Haas for suggesting me to study the issue of scale in the context of circular cities and introducing me to a research design that could potentially provide more insights about it. I also would like to thank all the interviewees that have participated in the research and took time to reflect upon my material and answer my questions.

I cannot omit the fact that this research has been carried out while I was living abroad, which has influenced the overall process at a personal level in a very positive way. For this, I would like to thank all my friends in Wageningen and Rotterdam for accompanying me throughout the journey, but most specially Belén, Lies and Jorrit. I would also like to thank my friends from Barcelona for their interest and support and Alejandra for having visited me multiple times in the Netherlands and having been very present in my life despite of the distance.

Finally, I would also like to acknowledge the key role that my parents have had in the completion of this thesis. I would like to thank them their extreme generosity and unconditional support they have always shown.

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LIST OF ACRONYMS

GHG	Greenhouse gas
LCA	Life-cycle assessment
MFA	Material flow analysis
EMF	Ellen MacArthur Foundation
EEA	European Environment Agency
SFA	Substance flow analysis
EF	Environmental footprint
MCA	Multi-criteria analysis
UHA	Urban harvest approach
STA	Sustainability technology assessment
ME	Metabolic efficiency

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SUMMARY

Cities and other urban environments already host more than half of the world's population and this fraction is only expected to increase with an additional inclusion of 2,5 billion inhabitants by 2050. This concentrates intensive human activities in reduced land extents and poses substantial environmental pressures. To improve the sustainability of cities, addressing the cycles of organic nutrients is crucial. Cities aggregate biogenic materials and their nutrients because food is imported from agricultural lands and processed inside the urban boundaries. This generates different biogenic wastes on-site. The nutrients found in the waste are rarely recycled and this increases the use of artificial fertilisers in agricultural lands. Moreover, the nutrients' economic value is also lost through down-cycling processes such as incineration.

The circular economy, which is an emerging economic model, strategically decouples economic growth from resource consumption to improve the sustainability of human activities. One of its principles consists in regarding waste as a resource. This is of interest if applied to urban biogenic waste streams because they are rich in nutrients and higher compounds that could be used to produce goods that are currently obtained through the exploitation of ecosystems and fossil fuels. Moreover, cycling organic nutrients back to the biosphere would contribute to balance the disrupted global elements' cycles. The many approaches to circular biogenic streams that are applied in urban areas can be classified at three different scales: circulating the nutrients at a household or building level (micro-scale), at the neighbourhood or district level (meso-scale) and doing it at the city wise, metropolitan area level (macro-scale). Many circular technologies are becoming available at each scale, but the limitations of current circular economy assessment methods do not allow to compare alternatives simultaneously. As a result, the most appropriate scale to implement a circular economy in urban settings is poorly discussed.

Amsterdam expressed its ambition to move towards total circularity by 2050 through signing the City Deal and thus, many initiatives at the micro-, meso- and macro- scales can be found within the city boundaries. Moreover, Amsterdam urgently wants to improve the circularity of biogenic waste flows because its urban characteristics impede the successful separation and recovery of biogenic materials. Therefore, Amsterdam has been used as a case of study to develop a tool to assess the extent to which circularity principles are met by different initiatives. The main research focused on comparing innovative technologies' performance in terms of circularity.

The assessment tool included a Performance Matrix in which 20 criteria appraise the performance of six micro-scale technologies, seven meso-scale technologies and fourteen macro-scale technologies. The selected technologies were mapped and their performance was determined through literature review and expert interviews. This resulted in a combined technology inventory. The literature review and expert information also defined a set of criteria that contained the most relevant characteristics of a circular economy of biogenic waste in the context of Amsterdam. Every technology's performance was scanned through these criteria and the resulting Performance Matrix identified common strengths and weaknesses of the technologies implemented at each of the scales. These research methods depend on collecting secondary data (theory building through literature reviews) and primary data (data collection

through expert interviews) distinguishing two phases of research that have mutually influenced each other.

The Performance Matrix enabled a systematic comparison among the three scales. Micro-scale technologies reduced environmental, economic and societal impacts but did not fully match Amsterdam's context because its urban characteristics its urban characteristics do not allow to separate different streams, the used products are not appealing to locals and the technologies are difficult to trace. Moreover, the technologies' potential benefits are only obtained if its use adds momentum cumulatively. Meso-scale technologies strongly reduced environmental and economic impacts. Its volumes are appropriate to obtain a wider range of added-value products but they current focus on energy carriers' production, which annihilates nutrients and functional building-blocks in the combustion. Finally, analysing macro-scale technologies revealed the further development of sustainability assessment tools to decrease its chemical and energy intensity and its rebound environmental effects. Nevertheless, the available macro-scale technologies are more numerous and produce more by-products that are also more interesting for local stakeholders.

Overall, my research informed by a non-data intensive approach, designed to analyse circular systems and able to compare several alternatives simultaneously, helps to streamline the necessary discussion about the scale at which circularity of biogenic waste can be better approached.

1. INTRODUCTION

1.1. Background

Circular Economy (CE) is an emerging economic model that has gained increasing attention during the last decade as a promising means to achieve sustainable development (Ghisellini, Cialani, & Ulgiati, 2016). It differs from the current predominant economic models, based on linear processes composed by a sequence of extraction, production, consumption and disposal steps and pay little attention to environmental and social pressures (Sauvé, Bernard, & Sloan, 2016). CE approaches sustainable development by decoupling economic growth from resource consumption and promotes waste minimisation by conceiving end-of-life materials as a resource rather than a residue (Elia, Gnoni, & Tornese, 2016). CE is thus a broad concept that can be used as a framework of design in different domains, such as policy instruments, value chains, closed-loop material flows, product-specific applications, and technological, organisational and social innovation (Winans, Kendall, & Deng, 2017). Transitions from linear to circular economies are aligned to Transition management theories, which consist in multi-level models that distinguish between innovation in niches, dominant regimes, and external landscapes (Loorbach, 2010). Accordingly, when it comes to the design of CE systems, three different levels are addressed: the micro-, meso- and macro- levels. The micro level refers to single companies, products and customers; the meso- level addresses industrial parks and neighbourhoods and the macro- level focuses on cities, regions and nations (Elia et al., 2016; Ghisellini et al., 2016; Sauvé et al., 2016).

The development of a CE in urban systems is being increasingly regarded as a way to decrease the environmental pressures caused by cities through more efficient use of resources while also supporting the economy (Kalmykova & Rosado, 2015). Because cities host intensive human activities and face rapid socioeconomic development, they frequently deal with serious ecological and environmental challenges: for instance, they are responsible for the consumption of three-quarters of the world's natural resources and 60 – 80% of all GHG's emissions (Grimm, Grove, Pickett, & Redman, 2008). Moreover, cities accumulate biological materials within their boundaries due to the uptake of nutrients proceeding from rural areas to support the lives of their inhabitants. Since these materials are rarely returned to agricultural systems, the imbalance of inputs and outputs turn cities into concentrators of organic waste materials, which originates large amounts of organic waste and other negative externalities (Ellen MacArthur Foundation, 2017). The recovery of post-consumer nutrients and its circulation within the economy has the potential to reduce environmental pressures and the demand for exploitation of nutrients from non-renewable sources (Figure 1). Cities present great opportunities to implement these circular principles in its biological cycles due to high proximity between stakeholders, large scales of biogenic waste supplies and technological infrastructure. Yet opportunities exist, the mechanisms for shifting towards a more circular model of biogenic waste in urban settings has been largely unexplored so far (Ellen MacArthur Foundation, 2017).

Figure 1. Value pyramid of circular strategies related to biogenic waste. Source: Adapted from ChainCraft B.V.

The rise of innovative technologies that enable the recovery of valuable materials from biogenic waste streams has opened the discussion about the scale at which biogenic material flows are more effectively circularised. In the past, health and hygienic urban problems were very successfully solved through centralized infrastructure but now they are environmentally and technologically challenged by smaller scale, more effective designs. Large-scale, centralised systems benefit from increased supply and demand, greater economies of scale, and easier and greater supply of secondary raw materials (Christopher Kennedy, Cuddihy, & Engel-yan, 2007). On the other hand, a great benefit of decentralization lays on the fact that it leaves room for more innovative treatments and has the potential to deliver essential services such as water, sanitation and waste management, healthcare and education in a more effective manner. In the context of waste management, the appropriate scale of approach might vary depending on the material flow: it was found that waste with high market value and relatively low costs of transportation is better circulated in larger scales, while waste with low market value and high costs for long-distance transportation, such as organic or demolition wastes, are more suitable for smaller scales of recycling and recovery (Chen, Fujita, Ohnishi, Fujii, & Geng, 2012). Despite the importance of the scale in the waste management approach, very few studies analyse urban metabolism at multiple scales or have applied its techniques in practice and thus, a discussion about the most appropriate scale of circular solutions for urban flows is often disregarded (Zhang, Yang, & Yu, 2015). Moreover, interactions between smaller scale levels and greater urban region infrastructure also needs to be taken into account if optimal local management technologies need to be identified (Kennedy, 2007). The micro-, meso- and macro- level defined for this research are aligned with the following definitions:

- Micro level: When the recovery of biogenic materials occurs within the boundaries of a household, a building or a street thanks to the implementation of small-scale technologies which are not connected to centralised infrastructure;
- Meso level: When the recovery of biogenic materials occurs within the boundaries of a neighbourhood or a district, thanks to the implementation of medium-scale technologies which are not connected to centralised infrastructure;

- **Macro level:** When the recovery of biogenic materials occurs within a metropolitan area thanks to the implementation of large-scale technologies which can be connected to the centralised infrastructure.

Evaluating the performance in circularity terms of innovative technological solutions is still a pending issue. Even the increasing attention CE has gained in the recent years, meta-analyses show that a deep research on CE assessment and circularity indicators is still lacking (Elia et al., 2016). For instance, Ghisellini et al. (2016) found that only 10 out of 155 reviewed studies focused on the design or discussion of indicators for the assessment of CE strategies. Environmental impact analysis methods such as Life-cycle Assessment (LCA) or Material Flow Analysis (MFA) are commonly applied to asses de sustainability of CE designs, but they still present major drawbacks. Firstly, these methods were conceived to assess linear processes and are not originally designed for the systemic, closed-loop and feed-back features that characterizes CE designs (Yong Geng, Joseph Sarkis, Sergio Ulgiati, 2013). Another major practical drawback is the need for extensive data sets, which, in the rare case this data is available, reliable and complete, results in costly and time consuming studies (Voskamp et al., 2016). Finally, such methods do not have the capacity to judge the sustainability of a system in comparison to alternatives and its results are highly case-specific (Zhang, 2013).

1.2. Problem definition

Cities are projected to host 60% of world's population by 2030 (United Nations, 2016). Besides of coping with challenges related to mobility and housing, cities will also need to reintroduce their outflow of biological nutrients back to the nature or cycle these nutrients within their economic systems to alleviate the environmental pressures caused by nutrient aggregation and reduce their dependency on fossil fuels. Yet CE models propose varied strategies to achieve an effective cycling of nutrients and many innovative technologies are emerging in the city, the scale at which circular design of biogenic material flows is approached is rarely discussed. One of the reasons is that the methods to assess the performance of technological innovations that enable the circularity of these nutrients present some limitations, such as not being able to compare more than one alternative simultaneously, being too data intensive and highly resource-consuming and failing at capturing all the dimensions of circularity for being designed to assess linear processes. Thus, the degree to which CE principles are satisfied by implementing circular technologies at each of the scales remains difficult to evaluate.

1.3. Aim of the study and research questions

This thesis aims to design a tool to systematically assess the extent to which CE principles are fulfilled by three different scale approaches to urban circularity: the micro- scale, which recovers the biogenic materials at the household, building or street level; the meso-scale, in which the recovery takes place at neighbourhood and district level; and the macro- scale, that does it within a city or its metropolitan area. This tool is to be designed and applied within a case study. The technologies found in the specific area are mapped and classified by scale. A set of criteria specifically defined for the case study area are the judging elements for the technologies. The mapped technologies and the criteria will be combined in a Performance matrix to assess the performance of each technology against each criterion. A qualitative scale is used to score each technology against each criterion based on information obtained in several literature reviews and unstructured expert interviews to avoid the need of using substantial amounts of quantitative datasets. Finally, the analysis will enable a discussion about the performance in terms of circularity at the scale level by identifying common strengths and weaknesses among the technologies belonging to each one of the three different scales.

Hence, this research aims answering the main research question: "*How does the performance of innovative technologies implemented at the micro- meso- and macro- scales compare in terms of circularity?*" The following research sub-questions guided the research:

RsQ-1. Which technological innovations at micro-, meso- and macro-scale can contribute to the circularity of household biogenic waste flows?

RsQ-2. What are suitable criteria and indicators to determine the circularity of these technologies?

RsQ-3. How do these technologies perform on these circularity criteria and indicators?

Amsterdam has been chosen as a case study. This city has various characteristics that make it suitable to apply this assessment. Firstly, the city performs poorly in terms of biogenic waste recovery with a recovery rate of only 3% for biogenic household waste while 97% is burned for energy recovery (Circle Economy, 2015). Secondly, Amsterdam is one of the eight Dutch municipalities that signed the ambitious City Deal programme, so that full circularity is to be achieved in the city no later than 2050 (Ministry of Internal Affairs, 2015). This also makes of it a useful study case for two reasons: Firstly, a large literature availability in form of policy documents and reports that further operationalise the envision of a CE for the city. Secondly, the relatively high prevalence of circular technologies applied at different scales, such as De Ceuvel circular playground, the circular Buiksloterham district or the Greenmills circular industrial cluster. Thus, the relatively high alignment of Amsterdam's institutions along with CE principles make of the city a relevant and feasible case study for circularity assessment.

1.4. Case study: Amsterdam

Amsterdam is the most populated municipality in the Netherlands and earns the status of the capital of the country. Data from the Amsterdam municipality indicates that the metropolitan region of Amsterdam holds 2,4 million inhabitants, 822.272 of those living in the city of Amsterdam itself (Gemeente Amsterdam, 2015). Thus, the city accounts with 442.693 households and the prospects are for this numbers to increase around 900.000 inhabitants 500.000 households in the coming years (Gemeente Amsterdam, 2015). The expected increase population will make increase the amounts of waste produced, together with the need for new and innovative waste management systems (Figure 2.).

A remarkable urban characteristic of Amsterdam influencing waste management is the fact that 88% of the buildings are high rise homes, with limited residential areas and limited access to outdoor spaces (Gemeente Amsterdam, 2015). Thus, the average surface of a property is between 70 and 80 m2 and only 10% of the households have a garden (Gemeente Amsterdam, 2015). It is important to consider this because the size of a property appears to be decisive for the separation of waste carried out by residence. Small spaces demand for diverse ways of waste separation indoors since, for instance, residents of apartments without garden do not have the option to place mini-containers outside their houses. Moreover, Amsterdam's limited public space makes it complicated to separate waste, especially in the densely-populated areas of the city. The above ground space is required by the citizens and the space underground holds a network of cables and pipes. Thus, finding a way to manage the waste processing is already a challenge due to the urban characteristics of the city (Gemeente Amsterdam, 2015).

These physical challenges imposed by the public space strongly explain the relationship of Amsterdam citizens with their waste. An average Amsterdam citizen produces a total of 370 kg of solid waste per year (Gemeente Amsterdam, 2015). Up to 27% of this solid waste is collected separately; either in containers (paper, glass, plastic and biodegradable matter), shops (electronic devices, light bulbs, batteries…), and "Wastepoints" (Afvalpunten). The remaining 73% of the city waste, including solid biogenic waste, is incinerated and used for power and heat generation in the AEB waste-to-energy plants, where only metals such as iron, copper or aluminium are recovered from the ashes (Jonkhoff, Kalma, & Kooij, 2012). The energy provided by the incineration process supplies many Amsterdam's homes and businesses with electricity and heat (Jonkhoff et al., 2012).

The overall sewage sludge production in the Noord-Holland province is of 154.000 tonnes (CBS, 2017). With a population of 2,762 million people, it can be roughly estimated that the average production of black water per Amsterdam citizen becomes 55kg/year. A single flow containing black water and grey water is then coming out from households and streamed through a network of 4.000 km of pipes that also collect water from non-household buildings towards a centralised treatment plant managed by the company Waternet. There, the flow undergoes a sanitation process that enables the water to be released back to surface water bodies.

Figure 2. Overview of the urban area selected as a case study. Source: Google Maps.

1.5. Overview of the content

The thesis is composed of seven chapters that follow the research process itself. Chapter 2 includes an explanation of how the methods used during the two distinct phases of the research process provided the answers to the research questions. Chapter 3 lists the 26 identified technologies in an Inventory of technologies classified by micro- (Section 3.2.), meso- (Section 3.3.) and macro- scales (Section 3.4.) within the Amsterdam metropolitan region. This includes a brief description of the inputs, outputs and the transforming process that each technology uses. Chapter 4 introduces the concept of CE (Section 4.1.), the operationalisation of it in the context of Amsterdam (Section 4.2.) and the derivation of a Table of criteria to assess the circularity of technologies found in Amsterdam (Section 4.3.). This chapter also includes the results of a literature review of existing assessment methods and a reflection about the extent that these methods capture all the aspects considered in the Table of criteria (Section 4.4). Chapter 5 presents the Performance matrix, which scanned the technologies against 20 derived criteria. The conclusions from this exercise are combined with the insights from 5 different interviewed experts and the main strengths and weaknesses for each scale are discussed. Chapter 6 discusses the overall findings with respect to the research questions and the overall validity of the research. Chapter 7 presents the conclusions of the thesis.

2. METHODOLOGY

This chapter presents the methods used throughout the research process. Section 2.1. provides an overview of the whole research. Then the structure of the research is divided into two differentiated phases: Section 2.2. includes an explanation of the first phase, and the methods based on secondary data collection. Section 2.3. includes the methods applied during the second phase, based on primary data collection and how these helped further answering the research questions.

2.1. Overview of the research process

The study starts with the formulation of the following main research question: *How does the performance of innovative technologies implemented at the micro- meso- and macro- scales compare in terms of circularity?* This was raised to carry out a systematic comparison about the strengths and weaknesses of cycling the nutrients contained in household biogenic materials at each of the three mentioned scales. Both primary data and secondary data have been collected to conduct this research, which marks the two main phases of the research process. In a first phase, a preliminary Table of criteria, preliminary Inventory of technologies and preliminary Performance Matrix were built, mainly based on information obtained by means of a literature review. The literature review process was performed with Google and Google scholar browsers, the on-line search engine from the WUR library and the Elsevier ScienceDirect on-line data base. The documents used were peer-reviewed articles, policy documents and open reports from research centres or consultancies. In the second phase, the outcomes of the first assessment were presented to experts by means of unstructured interviews. These experts discussed and validated the results and provided additional input. The research process has been iterative since it implied going through the research phases twice. The fact that the second phase affected the results of the first phase is a trait commonly observed in abductive research processes which go beyond the research patterns of abduction or deduction, where theory building and data collection interact and affect each other. An overview of the research process can be observed in Figure 3.

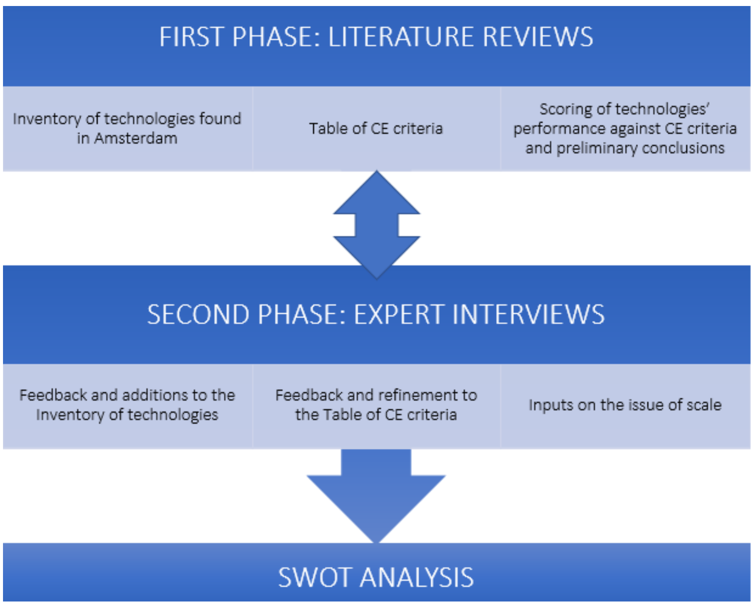

Figure 3. Overview of the research process.

2.2. First phase: design and application of an instrument

2.2.1. Which technological innovations at micro-, meso- and macro-scale can contribute to the circularity of household biogenic waste flows?

The purpose of this question was to build up a set of innovative and existing technologies found within the Amsterdam metropolitan region that could recover household biogenic waste flows. This question was firstly answered by means of literature review. The report from Brolsma & Leeuwen was used as initial input of technologies and then more alternatives were added based on reading of reviews of technologies that enabled the recovery of organic waste. Some additions were also made, based on the attendance of two academic workshops. The first was the SENSE Workshop Circular Economy celebrated in The Hague the 13th of March of 2017. The second was, the Circular Cities Masterclass offered by the consultancy Metabolic on Saturday 17th June of the same year in the Amsterdam-based circular playground *De Ceuvel*. The outcomes of this research were a preliminary Inventory of technologies including 26 items sorted into a first level of classification regarding the scale 6 at the micro-, 5 at the meso-, 15 at the macro- scales. The table including the preliminary Inventory of technologies can be found in the Appendix (Table 1.2)

2.2.2. What are suitable criteria and indicators to determine the circularity of these technologies in Amsterdam?

The purpose of this second question was to identify a suitable instrument for analysing the performance of the set of technologies implemented at different scales of management. Two options opened: either selecting one instrument that already existed or build a new instrument for the specific purpose of this study. To decide in between these two options, two parallel literature reviews were carried out: firstly, one that allowed the conceptualisation of an applied CE of biogenic flows in Amsterdam and a second literature review on existing assessments that could include all the principles of such a concept.

The first literature review included the examination of documents from the Ellen MacArthur Foundation (EMF), the leading organisation in championing the potential of the CE for EU economies (Gregson, Crang, Fuller, & Holmes, 2015); the document *"Circular Economy in Europe: Developing the knowledge base"* from the European Environmental Agency (EEA), that included the most relevant policy questions for materials' cycling in a European context and indicators to measure circular management systems; the document *"A Circular Economy in the Netherlands by 2050",* a joint publication of from various Dutch ministries specifying how the bureaus envision a CE in the Netherlands and the document *"Circular Amsterdam: A vision and action agenda for the city and the metropolitan area"*, a report that designs a circular scenario of organic waste cycling from the Municipality of Amsterdam and the consultancy Circle Economy. The underpinning purpose of this literature review was to narrow down a CE of biogenic waste from conceptual to specific by reading through the European-wise, national-wise and metropolitan-wise characteristics so that the maximum of characteristics that a CE of biogenic waste in Amsterdam would have could be captured. The examination of these reports was used to derive a preliminary Table of criteria that reflected the main aspects of concern to implement an effective CE for these institutions. For a neater appearance and a more user-friendly outlook, the resulting 23 criteria were clustered into 9 topics (Table 1.1. in the Appendix). All the criteria mentioned in each report were listed (Table 2.4. in the Appendix), and repetitive criteria were eliminated. The times a certain criterion was mentioned by a certain institution was tracked to obtain an impression of its relevance.

The results of the second literature review indicated that even though environmental impact assessment methods have been already applied to evaluate closed-loop designs, its application was not appropriate for current study due to many reasons. Firstly the methods require of large quantitative data sets that sometimes were not available or present different levels of aggregation (Voskamp et al., 2016), they are fundamentally designed to study one process at a time and are unable to compare different options, the methods were initially designed for linear processes and fail at capturing circularity valuable nuances (Yong Geng, Joseph Sarkis, Sergio Ulgiati, 2013), and failed at capturing economic or social impacts (Angelakoglou & Gaidajis, 2015; Patrício, Costa, & Niza, 2015). The outcomes of this literature review and an analysis of its appropriateness for this study can be found in Section 4.4.

2.2.3. How do these technologies perform on these circularity criteria and indicators?

Combining the outcomes of both exercises, a Performance Matrix was developed, similarly to matrices implemented in Multi-Criteria Analysis (MCA). MCA's are decision-making tools developed for complex multi-criteria problems that include qualitative and/or quantitative aspects of it and depict preferences between a set of alternatives for which measurable criteria have been stablished (Department for Communities and Local Government, 2009). There exist numerous MCA techniques, but a common core feature of any MCA is the construction of a Performance matrix in which each row describes an alternative and each column describes the performance of the each alternative against each criterion (Department for Communities and Local Government, 2009). The main feature for what it was decided to design a Performance matrix was its capability of simultaneously include multiple criteria and multiple alternatives, the capability of not requiring too large quantitative data sets, the possibility to incorporate both qualitative and quantitative information (Mendoza & Macoun, 1999). It was also convenient in the sense that the criteria of the Performance matrix could include all the elements present in a CE of biogenic household waste and could capture multidisciplinary values. The preliminary Performance matrix scanned the 26 technologies included in the preliminary Inventory of technologies (6 operating at the micro-, 5 operating at the meso- and 15 operating at the macro) against 20 criteria compiled in the preliminary Table of criteria, originating a preliminary set of conclusions.

The preliminary Performance matrix was designed with an Excel workbook. The scoring of each technological alternative was based on the findings on literature reviews from peer-reviewed paper and expressed qualitatively: each cell of the matrix was filled with one out of five colours from deep red to bright green, depending on how high the technology scored for that certain criteria. The colouring method was used so that patterns among different scales with regards to certain criteria would be easily identified. It was particularly useful to sort the technologies according to scale to have an overview of the commonalities found under this classification. The validity and reliability of the conclusions flowing from the preliminary Performance matrix were assessed by experts in the second phase of the research.

2.3. Second phase: Feedback from experts and validation of results

The second phase consisted in the collection of primary data and assessing the validity of the preliminary findings by interviewing experts. Five in-person meetings were scheduled with a total of 5 experts to provide feedback on a) the preliminary Table of criteria; b) the preliminary Inventory of technologies c) conclusions on the Performance matrix and give some additional input. Due to the exploratory nature of the research, it was decided to use a format of a semi-structured interview. This means that the set of questions to be addressed was defined as well as the aspects that the feedback should address. Nevertheless, the questions were open-ended and sometimes interviewees brought topics themselves. The reason for choosing this format was because it resulted a useful format to dig deeper into how effective the cycling of materials is implemented in practice, by formulating questions and raising issues on the spur of the moment.

Two of the experts worked in the management of innovation projects, belonging to Waternet and the Dutch water board of Rijn en Ijssel. The other three experts mainly carried out academic research and had a broad experience of involvement in projects outside from academia. Their area of expertise covered environmental technology, biomass value chains and water management (Table 1.4 in the Appendix). The experts received via mail the three preliminary documents related to the three elements of discussion addressed in the meetings (preliminary Inventory of technologies, Table of criteria and Conclusions) and an item list with the topics of interest to be addressed in the interview an average of one week prior to the meeting.

Notes from the conversation were taken during the interview and further elaborated on the same day in a digital document to minimize loss of information. Responses and corrections on the preliminary Table of criteria were integrated into final Table of criteria and arguments that discussed its validity are included in the Discussion chapter. Inputs on additional technological alternatives and corrections on the preliminary Inventory of technologies were later incorporated in the definitive version of the Inventory of technologies. These modifications affected the Performance Matrix as well, that was enlarged by these additions. Outputs from the interviews related to the item list of discussion of the interviews were clustered into topics and (Section 5.2.) The item list can be found in the Appendix (Table 1.5.).

3. INVENTORY OF TECHNOLOGIES

This chapter presents the Inventory of technologies. Section 3.1. defines the different biogenic flows that are addressed by the technologies. Section 3.2. presents a brief description of each technology, summarizing its required additional inputs and the outputs. Finally, section 3.3. presents some concluding remarks.

3.1. Household biogenic flows

The EMF distinguishes two main types of materials present in the economic systems: some of these consist of "biological nutrients", that will re-enter the biosphere after the product's life cycle and other and "technical nutrients", which are designed to circulate at high quality ideally without entering the biosphere. To be more specific, the focus of this study is put on household biogenic waste containing the biological nutrients. The term 'biogenic' refers *to any substance produced by life processes, which might be secretions or constituents of plants and animals*. This definition leaves other processed organic materials such as wood from furniture or recycled paper out from the scope of this study.

When analysing the biogenic fractions that come out from a household, it was found that they are present both in solid waste streams and liquid waste streams (Brolsma & Leeuwen, 2016). This initial division based on the physical property of the material is used as a starting point for organising the selection of biogenic flows (Figure 4). It is important to note that the physical state of some fractions might change when coming out from the physical boundaries of the household. For instance, food waste might leave the household in a liquid phase if it is treated at source with a food grinder that mixes it with the household sewage sludge. Nevertheless, this classification will leave out the treatment at source phase and classify the waste according its physical properties without undergoing any treatment.

Within the solid waste stream, the simplest categorization of biogenic fractions from households which has been used by most waste composition analyses is the differentiation into garden waste and food waste (Lebersorger & Schneider, 2011)

- Food waste: Many classifications of food waste components exist. It contains preparation residues (discarded non-edible parts of ingredients), post-preparation and post-consumption residues, partly consumed food (not whole as purchased) and whole unused food (Lebersorger & Schneider, 2011) originated in households. Food waste is composed by a broad variety of food categories that include both animal and vegetal origins, and both processed and unprocessed ingredients. Dairy products, eggs, fruit and vegetables, bakery products, meet and fish, pet products, deserts, sauces and other condiments make of household food waste a very wet, nutrient-rich stream with high contents of proteins, sugar and lipids. This stream presents considerable challenges due to its highly putrescible nature and the environmental, public health, and amenity implications.

- Garden waste: It comprises the fraction of non-edible vegetables originates in the green spaces of the household. This includes fine garden residues such as leaves or grass and coarse garden residues such as stumps, large branches or scraps from pruning (Brolsma & Leeuwen, 2016)

Biogenic fractions are also encountered in liquid phases coming out from households:

- Black water: Organic residues are produced after nutrients' intake and water is absorbed by humans to support their vital needs. It is an important fraction since it contains high concentrations of macro-pollutants such as P or N. In urban environments where urine and faeces are streamed together with the municipal sewage sludge, black water accumulates the 91% of the total nitrogen and 79% of the total phosphorus of the overall load in the inflow of a purification (Brolsma & Leeuwen, 2016). In addition, black water also contains undesired elements such as pathogens, drug residues, hormones and heavy metals. It is important to consider the possible further separation of this steam into the following sub-fractions: Brown water, consisting in the faeces; Yellow water, which is the urine. As a relatively concentrated stream, it has potential for nutrients and energy recovery (Zeeman et al., 2008).

- Grey water: Grey water originates due to the activities that support human living, mostly related to hygiene. This is a flow that collects the streams of running water coming from the shower, bath, laundry and kitchen (Zeeman et al., 2008). Personal care products, soaps and detergents are mostly diluted in the grey water at a relatively low concentration. As a relatively diluted stream, its potential for recovery is mostly directed to energy (Zeeman et al., 2008).

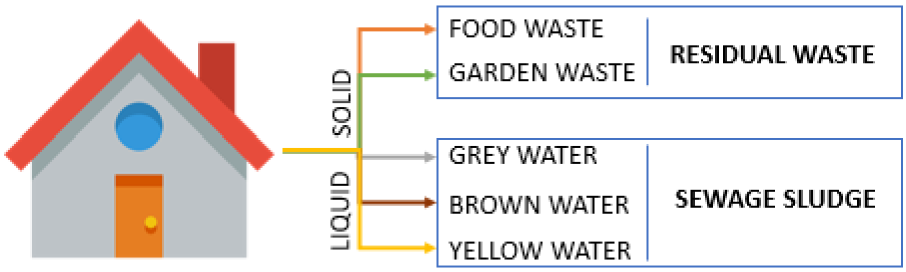

Figure 4. Overview of the main househld biogenic flows included in both the solid and liquid fractions.

3.2. Micro-scale technologies

Bokashi bins (Anaerobic digestion – partially inhibited)

Anaerobic digestion (AD) is a process to biochemically decompose both liquid and solid organic matter by various bacterial activities in an oxygen-free environment. The anaerobic biodegradation of complex organic matter to CH_4 and CO_2 consists of a series of microbial processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The final methanogenic steps of the AD process can be fully inhibited, thus obtaining volatile fatty acids, CO_2 and H_2 instead (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017a). These inhibited process is carried out by indoor composting bins and enable the digestion of kitchen waste, obtaining a solid fraction of relatively stable compost and an amount of leachate that can be diluted in water and applied to plants.

Composting bins (Aerobic composting)

Composting involves the controlled aerobic decomposition of organic matter that results in a stable organic end-product called humus. Many types of organic solid wastes are suitable for composting, including yard waste, food waste, agricultural waste and animal manure (Lohri et al., 2017a). At the appropriate conditions, microorganisms and invertebrates carry out the process, consisting of three main phases: (a) Mesophilic phase, which lasts for a few days; (b) Thermophilic phase, in which the metabolic activity of microorganisms causes a temperature rise to 55-70 °C; (c) Cooling and maturation phase, in which the substrate's inner temperature lowers to the point it reaches the ambient temperature and generally lasts for several months (Lohri et al., 2017a). The main product from composting is compost, but other minor products are emitted during the process, such as leachate, carbon dioxide and water vapour (Lohri et al., 2017a).

Domestic wormeries (Vermicomposting)

Vermicomposting is defined as an aerobic process of organic waste degradation and stabilization by interaction of microorganisms and earthworms under controlled conditions (Lohri et al., 2017a). Thus, microbes degrade organic matter and a community of earthworms then feed on the microbial waste, resulting in the generation of vermicompost. This process can be done at the household scale by means of commercial wormeries. Commercial wormeries are piles of around 70 litres divided by different trays that enable the process in a progressive way.

Low-tech biofilters (Biofiltration)

Grey water can undergo individual treatment with low-tech biofiltration in household water treatment systems to achieve sufficient water quality for discharge into the ground based on Dutch regulation (Roest, Smeets, van den Brand, Cortial, & Klaversma, 2016). An example of such technology is taken from the project implemented at De Ceuvel in Amsterdam. In this case, houseboats' grey water system was designed to be disconnected from the centralised pipeline and they were provided with an individual grey water treatment unit before releasing to the water canals. These units consisted of two pallet tanks filled with a mixture of gravel and sand, topped up with reed and achieved the required standards of purification to release the water back to surface streams (Roest et al., 2016).

Composting toilets (Aerobic composting)

Composting toilets are alternative technologies to process black water flow that require no fresh water and can therefore disconnect the toilet from both the water supply and wastewater infrastructure. An additional advantage of composting toilets is the possibility to cycle nutrients (use of faeces as fertilizer) and offer good promise as sustainable solutions (Anand & Apul, 2014). At the cleantech playground De Ceuvel, composting toilets were used in the office boats, so the users had to bring the faecal matter from the composting toilet periodically to a central composter. After 11 months composting, the level of streptococci in the composter was reduced by log 1.9, which failed at meeting the WHO recommendations (Roest et al., 2016). Furthermore, user satisfaction regarding the composting toilets and the handling of human excreta turned to be low, while the costs become higher compared to other (conventional) sanitation solutions. Following the experience, application of composting toilets was not recommended in future developments in the context of Amsterdam (Roest et al., 2016).

Waterless urinals (Small-scale struvite precipitation)

A waterless urinal at De Ceuvel collected pure urine and stored it in two buffer tanks. Nutrients were recovered from the urine using struvite precipitation and adsorbent materials to generate fertilizers that were used for local production of tomatoes. The process recovered approximately 98% of P and 10% of N (Roest et al., 2016). The concentration of pharmaceuticals in tomato biomass was below detection limits, far below the acceptable daily intake so that made them safe as soil enhancers. The struvite performed successfully as a fertiliser for locally grown tomatoes.

3.3. Meso-scale technologies

Worm containers and worm hotels (Vermicomposting)

Le Compostier initiates community composting projects in Amsterdam by designing and building wooden worm composting containers. The devices are named Worm Hotels and are provided with a space on top of the Worm Hotel for growing plants for food and local pollinators. The projects do not only close the loop of food but aim at improving the soil of Amsterdam, stimulating local food production while preventing pollution and to empowering local people by jointly creating value from their organic waste and providing informative workshops on how to create a greener and healthier city (Le Compostier, n.d.). Another initiative taking place in Amsterdam is the Buurtcompost Foundation. This entity, together with the municipality of Amsterdam and the Amsterdam University of Applied Sciences (Hogeschool van Amsterdam) have developed an underground worm container. Due to the constant temperature of the soil, the foundation highlights that composting takes place in all seasons evenly and without external intervention (Buurtcompost, n.d.).

Biomeilers (Aerobic composting)

A Biomeiler pile was installed in the Green Living Lab of Amsterdam. Biomeilers are medium-scale systems that undergo aerobic composting processes which produce heat due to the thermophilic phases they undergo. This heat is recovered by means of a system of running water that enters the pile and captures the heat that is being released. Thus, compost is produced as well as hot water. A container holding 50m^3 of woodchips soaked with water hold an installation of an 800-metre-long water pipe placed within the pile. The decomposition of the woodchips originates heat (up to 70ºC) that heats up the water of the pipe placed under the floor of the dome. The pile can be integrated into the urban landscape by supporting a small terrace on the top of it, for instance (Amsterdam Smart City, n.d.).

Nieuw West process (Anaerobic Digestion + Aerobic Composting)

Around 3300 homes in the Nieuw-West separate vegetable, fruit and garden waste collected by means of mini-containers in the garden. The achieved separation rate here is at approximately 43%, which is close to the national average of 48%. After collection, the collected organic waste undergoes anaerobic digestion, obtaining biogas that can be used for the generation of electricity and/or heat. The product that remains can be composted (Gemeente Amsterdam, 2015).

Buiksloterham grey water installation (Neighbourhood scale biofilters)

Large scale biofilters (constructed wetlands) are engineered systems that have been constructed to take advantage of the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in wastewater treatment. They can be applied to all types of wastewater including sewage, industrial and agricultural wastewaters, landfill leachate and storm water runoff (Vymazal, 2010). They require very low or zero energy input and, therefore, the operation and maintenance costs are much lower compared to conventional treatment systems. In addition to treatment, constructed wetlands are often designed as dual- or multipurpose ecosystems which may provide other ecosystems services such as flood control, carbon sequestration or wildlife habitat (Vymazal, 2010). A constructed wetland-based system was installed in the Amsterdam neighbourhood of Buikloterham. It first recovers the heat from grey water (which in average presents a temperature of more than 25 degrees), which is then returned into the household. The grey water is then purified by channelling it through a biofilter and then returning to surface water bodies (Waternet, n.d.).

Buiksloterham black water installation (Vacuum toilets combined with anaerobic digestion)

The homes from Buiksloterham have separate vacuum pipes installed to vacuum toilets. The vacuum toilet discharges the black water in a more concentrated way. By doing this, fresh water is saved and heat from grey water can be recovered thanks to a heat exchanger. The vacuum lines stream the black water towards a de-centralised fermenter installed in the district, where biogas is produced through anaerobic digestion. This biogas will be later converted into electricity, which can be used in households or also to run electric cars. An additional advantage of separating the liquid fractions of liquid biogenic waste in Buiksloterham is the possibility to precipitate struvite from the yellow water, which can be recovered and used as fertilizer. A similar installation is built in the neighbourhood of Eva Lanxmeer, located in Culemborg (Waternet, n.d.).

3.4. Macro-scale technologies

Black soldier fly treatment (Protix process)

In Amsterdam, the company Protix develops ingredients for animal nutrition based on insects grown in food waste. More concretely, the company uses cultures of black soldier fly larvae and produces food for a wide variety of animals, ranging from chickens, dogs, piglets or fish (Protix, n.d.). Nevertheless, an essential aspect needs to be considered: the food substrates need to come together with the GMP certification to guarantee that the products comply with quality and safety measures. The company currently uses certified food waste streams from supermarkets.

Production of furans (Superheated steam combined with biphasic reactor)

This process enables the production of bio-aromatics from household waste, cellulose (or hemi-cellulose) contained in the organic fraction. Biorizon's "Sugars to Aromatics" project focuses on converting sugar-rich biomass into furans: semi-finished products which serve as the basis for subsequent reactions to synthesise bio-aromatics or other "green" building blocks (Groen, 2016).

Medium-chain fatty acids production (Fermentation)

Medium-chain fatty acids (MCFA) are interesting compounds for being building blocks of food and feed, flavours and fragrances, polymers, plasticizers, paint and coatings and lubricants. (Grootscholten, Strik, Steinbusch, Buisman, & Hamelers, 2014) These are produced in Amsterdam by Chaincraft, a company that obtains the volatile fatty acids from anaerobic digestion of food waste and process them through a fermentation step, which allows the production of MCFA.

Ethanol production (Fermentation)

Fermentation is a process that enables the production of bio-ethanol, which can be applied as biofuel. Bioethanol can be produced from several sugar starch and lignocellulose based biomass by means of different conversion technologies (Lohri, Diener, Zabaleta, Mertenat, & Zurbrügg, 2017b). Single-sugars, starchy materials and lignocellulosic biomass are appropriate inputs. For lignocellulosic materials, the involved technologies are more complex and the costs are higher due to the lower digestibility of the lignocellulose and because it requires delignification pre-treatment. On the way to cost-effective and competitive bioethanol production from lignocellulosic feedstock several challenges remain such as developing more efficient pre-treatment technologies (Lohri et al., 2017b). Cargill is an Amsterdam-based company that can carries out this process (Cargill, n.d.).

PHA production (Avantium process)

One available type of bioplastics is polyhydroxyalkanoates (PHAs) that are polyesters accumulated in bacterial biomass as storage compounds. These properties are comparable with the properties of petroleum-based thermoplastics. The most common commercial PHAs consists of a copolymer PHB and PHV together with a plasticizer/softener and inorganic additives such as titanium dioxide and calcium carbonate (Environment Australia, 2002). PHAs are currently produced on commercial scale based on sugars, like food-processing wastes as molasses and whey or starch-containing agricultural or food-processing wastes could also be used after chemical or enzymatic hydrolysis of starch (Ivanov, Stabnikov, Ahmed, Dobrenko, & Saliuk, 2014). Monosaccharides for PHA synthesis can be produced from lignocellulosic materials to reduce the cost of raw materials. Especially for waste water processing plants producing PHA is promising (Brolsma & Leeuwen, 2016).

Transesterification

Greenmills is a consortium of several companies which has built a biodiesel plant in the Port of Amsterdam and runs on used cooking oil and used oil obtained from various catering establishments, slaughterhouses (residual fat) or food. The plant operates with high efficiency, which residues are minimized in the process and converted into high-end products. For instance, the residual potassium is converted to fertilizer. Furthermore, very low-grade fats are upgraded in the built-in purifying installation, before they go into the actual biodiesel process (Biodiesel Amsterdam, n.d.).

Anaerobic digestion (Orgaworld process)

Wet digestion technology is combined with biogas conversion technology to create electricity, heat and water purification in the Greenmills plant in Amsterdam. This facilitates smart synergies with the local heat network, the regional electricity grid and surrounding companies. Orgaworld Greenmills plant was launched in 2010 and processes nearly 120,000 tons of unpackaged supermarket food and other organic waste including 350,000 m3 of polluted waste water. The incoming organic waste is digested in large tanks, which releases. The biogas is converted into steam, heat and green energy. These products are partially used by Greenmills and the rest is released to the power network (Orgaworld, n.d.)

Sewage sludge treatment (Waternet process)

Grew water and black water together are directed via sewer conduits to central sewage treatment. Treatment steps are a) Separation against particle size (grids, settlement tanks, grease and oil traps) b) Aerobic purification with activated sludge c) N removal, anoxic tank, P removal. Biogas that is released during sludge fermentation at the RWZI is also conveyed to the AEB for the generation of electricity and heat. 11 to 12 kilo tonnes of phosphor on an annual basis. The average scale of a Dutch sewer drain treatment facility (RWZI) in the Netherlands is 66.000 residents (Brolsma & Leeuwen, 2016). Waternet has recently launched their plans to extract cold from its drinking water conduits to cool the blood bank Sanquin. The extraction will be mainly performed during winter will be used for the blood banks cooling systems in summer. Close cooperation has also been established in between AEB Amsterdam and Waternet. The former is providing AEB with 80 tonnes of dry sewage sludge per year, producing 11 million cubic metres of biogas that are burned in the installations of AEB, producing energy and heat. A part of it is returned to Waternet and 10% of this gas is used as biogas by OrangeGas (Circle Economy, 2015)

Energie- en Grondstoffenfabrieks

Energy and raw materials' factories are a result of a joint initiatives of the 21 Dutch water boards. Its focus in on the transformation of central sewage treatment plants into factories of energy and raw materials. Eight sewage treatment plants have already been transformed into Energy Factories, and nine more factories are on the way. Phosphate is already recovered at seven sites through struvite precipitation. Its plans are more ambitious, though. Products such as cellulose, alginate, CO2, bioplastics, biomass and fatty acids are targeted as interesting products to be obtained from sewage sludge and already pilot projects are already ongoing, offering promising results (Energie- en Grondstoffenfabriek, n.d.).

Power-to-protein

Power-to-protein is a process that can be coupled to wastewater purification treatments. The technology enables the production of high high-value protein (single-cell protein or SCP) via biosynthesis, using lithotrophic hydrogen-oxidizing bacteria in a reactor system. The main advantage of this technology is that N is upcycled to protein. This protein can be the used as feed additives in animal nutrition in the short term and has the potential to be used in human nutrition. Nevertheless, the system requires the following inputs: H_2, which can be extracted from wastewater thanks to a hydrolysis process that requires an input of electricity; NH_3, that can be recovered from the sludge treatment via air stripping; and CO_2, a by-product that can be obtained from numerous sources in urban and industrial environments (Power to protein, n.d.). According to a study carried out by Stichting TKI Water technology, coupling the technology to Amsterdam wastewater treatment implies an important potential due to an annual estimated production of 6300 tonnes of protein, covering the 36% of populations' protein needs. Nevertheless, additional inputs of H_2 and CO_2 are needed (Power, 2015). In January 2017, a pilot project was delivered a moved to a first research location in RWZI Enschede (Power, 2015).

Saniphos

The Dutch company GMB conceived the Saniphos technology to treat source collected urine. Its plant is successfully functioning since 2010 and presents a unique project for the recovery of nutrients from human urine. The Saniphos installation of GMB can process 5,000 m3 of urine per year, which is equivalent to more than 13 million toilet visits. The company received urine collected from music festivals taking place all over the country and from the programme "Moeders voor moeders" launched by its partnered pharmaceutical company MSD. The former provides GMB with residual urine from pregnant women that has undergone hCG hormone extraction to be used as active ingredient for fertility treatment of other women that want to become a mother (Kuntke, n.d.). After the extraction of the hormone, the remaining urine was collected and treated for the recovery of nitrogen and phosphate in the Saniphos process. Chemical analysis of the heavy metal content within the produced ammonium sulphate and struvite showed that their quality was in line with the European and Dutch quality standards needed for an application as fertilizer for agricultural purposes (Kuntke, n.d.). This project surpasses the Amsterdam boundaries but consists of an excellent example of how a large-scale infrastructure can become a successful case for nutrients recovery from liquid biogenic waste.

Pyrolysis

Pyrolysis consists of decomposing biomass by heat in the absence of oxygen resulting in the production of solid, liquid and gaseous products. From an economic point of view waste streams such as agricultural waste, pruning and roadside grass are the most attractive feedstocks for pyrolysis (Brolsma & Leeuwen, 2016). In the urban waste context, it results of special interest the lignocellulosic waste from carpentries, saw mills, park, garden waste and paper and cardboard. The main products of pyrolysis are char, bio-oil, and syngas. Some of the applications of char are fossil fuel, soil amendment and precursor for making catalysts and contaminants adsorbents. Bio-oil is a complex mixture of water and organic chemicals with more than 300 identified compounds and it presents a dark red-brown colour with a distinctive acid, smoky smell, and can irritate the eyes (Lohri et al., 2017a). Finally, the pyrolysis gas contains carbon dioxide, carbon monoxide, methane, hydrogen, ethane, ethylene, minor amounts of higher gaseous organics and water vapour. Other organics waste has also been successfully tested, such as agricultural wastes, energy crops, forestry wastes, sewage sludge and leather wastes (Lohri et al., 2017a).

Gasification

Gasification is a thermal treatment that converts carbonaceous material into syngas that can be used as fuel or to produce value-added chemicals (Lohri, 2017). While combustion oxidizes the carbon feedstock into water and carbon dioxide, gasification packs energy into chemical bonds by adding hydrogen and stripping away carbon from the feedstock. Suitable input materials are dry biomass (10-20% of moisture content) which requires biomass to be dried before gasification. Thus, the overall process is composed by the following sequence: (1) Drying, (2) Devolatilization, (3) Oxidation, (4) Reduction. The current most prevailing feedstock considered for biomass gasification is wood (Lohri et al., 2017b). Nevertheless, there is an interesting project called Waste2Chemicals to be started in the port of Rotterdam the first half of 2017. It consists of a gasification-based technology by Enerkem that converts non-recyclable municipal solid waste intro renewable chemicals such as synthesis gas and methanol (Clean Tech Delta, n.d.).

Waste-to-Energy plant (Incineration)

Waste incineration is a very robust waste management technology and can manage large ranges of waste types and material fractions in mixed solid waste (Astrup, Møller, & Fruergaard, 2009). In Amsterdam, the biogenic waste undergoes combustion in the AEB Waste-to-Energy plant, which supplies many Amsterdam's homes and businesses with electricity and heat. The high-value materials (both ferrous and non-ferrous metals) are recovered from the bottom ashes remaining after the incineration. Finally, the low-value bottom ash is used as filling material in road building or as a replacement for dredged sand in the ocean floors (Jonkhoff et al., 2012). AEB receives 1.4 million tons of municipal and industrial waste that is being delivered annually. The Waste-to-Energy plant operated by AEB processes 850.000 tonnes of the municipal solid waste (MSW) and the Waste Fired Power Plant (WFPP) processes 530.000 tonnes of industrial waste. From the processes, 1 million MWh of electricity are produced annually, that feed 320.000 households with electricity. Heat is also produced: 600.000 gigajoule a year over the last years. This heat is used for district heating: hot water and central heating of Amsterdam households

Landfilling

Landfilling consists in the disposal of waste material by burial and has been the oldest and most common method of organised waste disposal and it remains as such in many places around the world. Direct consequences of this practice are gas and leachate generation due primarily to microbial decomposition, climatic conditions, refuse characteristics and landfilling operations (Lohri et al., 2017b). The release of gas and leachate away from the landfill boundaries and their release present serious risks to the surrounding environment. Apart from health hazards, these concerns also include fires, explosions, vegetation damage, unpleasant odours, landfill settlement, ground water pollution, air pollution and gas emissions contributing to global warming (El-fadel, Findikakis, & Leckie, 1997). In 1995, the Dutch government issued a waste decree that introduced a landfill ban for 35 waste categories, including all combustible and biodegradable waste. As a result, no biodegradable municipal waste would under those circumstances go to landfill. Nevertheless, the provincial authorities can grant an exemption from the landfill ban to operators of landfills (for example, if there is a temporary shortage of incineration capacity) (Milios, 2013). Currently, the amount of biodegradable municipal waste (BMW) that is landfilled accounts for less than the 10 % of generated BMW in 1995.

Table 1. Inventory of technologies

MICRO-SCALE	MESO-SCALE	MACRO-SCALE
Bokashi bins	Worm hotels and containers	Black soldier fly treatment
Composting bins	Biomeilers	Production of furans
Domestic wormeries	Nieuw West process	Production of medium-chain fatty acids
Low-tech biofilters	Buiksloterham biofilters	Production of ethanol
Composting toilets	Buiksloterham vacuum toilets	Production of polyhydroxyalkanoates
Waterless urinals		Transesterification
		Orgaworld process
		Waternet process
		Energie- en Grondstoffenfabrieks concept
		Power-to-protein process
		Saniphos process
		Pyrolysis
		Gasification
		Waste-to-Energy plants
		Landfilling

4. CONCEPTUALISING A CIRCULAR ECONOMY OF BIOGENIC WASTE

The purpose of this chapter is to elaborate on the characteristics that a CE of household biogenic waste would present in Amsterdam. This is of vital importance with regards to the objectives of the study since defining well-stablished principles of circularity is a necessary previous step before assessing the extent to which the technological solutions satisfy these principles. For this, the results of a literature review including a brief overview of CE theories (Section 4.1.) and the principles of a CE envisioned by EMF, the European Environmental Agency (EEA), the Dutch government and the Amsterdam municipality (Section 4.2.) are used to narrow down the CE from a conceptual approach to the application in the Amsterdam context. In Section 4.3. a Table of criteria is derived from the combination of these inputs together with refinements and additions resulting from interviews. Having established what needs to be assessed, Section 4.4. contains the results from a literature review about common methods used in measuring circularity.

4.1. Overview of a Circular Economy

CE is a broad concept that can be used as a framework of design in different domains, such as policy instruments, value chains, closed-loop material flows, product-specific applications, and technological, organisational and social innovation (Winans et al., 2017). Creating a CE requires structural changes throughout all the phases of value chains, from product design and technology to new business models with the purpose to extend products' lifetimes and turning waste into a resource. The concept is interconnected with many fields, ranging from Systems theory (Ghisellini et al., 2016), Industrial Ecology (Ghisellini et al., 2016), Environmental sciences and sustainable development (Sauvé et al., 2016), Urban metabolism (Kalmykova & Rosado, 2015), eco-design among others, depending on the area of implementation.

The EMF defines the CE as "*an industrial economy that is restorative by intention and design. In a CE, products are designed for ease of reuse, disassembly and refurbishment, or recycling, with the understanding that it is the reuse of vast amounts of material reclaimed from end-of-life products, rather than the extraction of resources, that is the foundation of economic growth*"(Ellen MacArthur Foundation, 2013). The concept of circularity is based on the study of non-linear systems, particularly the living ones (Ellen MacArthur Foundation, 2013). The organisation identifies a loss of value and resources occurring all along the value chain of a product as a critical aspect of the current linear production model. To solve this, the organisation designed a restorative industrial system (Figure 5) including circular strategies that feed end-of life materials back into the beginning of production chains. Several frameworks have been developed to depict the principles of a CE in different contexts, such as the 6R model (reuse, recycle, redesign, remanufacture, reduce, recover) for manufacturing industries (Winans et al., 2017) or the ReSOLVE Framework for businesses and countries to become more circular (Ellen MacArthur Foundation, 2015).

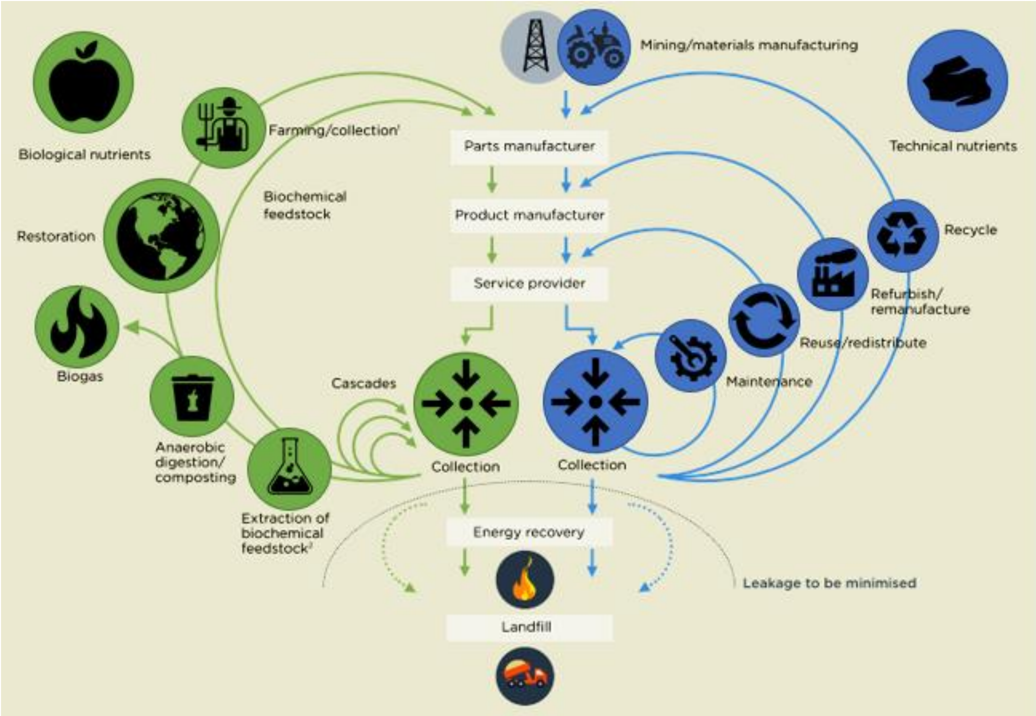

Figure 5. Scheme depicting the material loops within a CE. Source: Adapted from EMF.

The prevalence of CE initiatives has been increasing in the last decades and interestingly, each geographical area has emphasised certain aspects according to their country needs. Three main world areas are highly active in CE policies (Ghisellini et al., 2016; World Economic Forum, 2014) and are also more active in CE scientific literature production. Japan has been enforcing CE policies since the early 1970 to cope with the country's natural resource scarcity due to its geographical characteristics (World Economic Forum, 2014), being remarkably successful in the creation of 26 eco-towns (Ghisellini et al., 2016), the exhaustive tracking of its flows and the implementation of numerous CE policies around the concept of a 'sound materials cycle society', reaching a metals' recovery rate of 98% and with only 5% of their materials going to landfills (World Economic Forum, 2014). Europe stands out for being pro-active in the circular shift and CE measures can be found in various environmental and economic policies (World Bank, same link). While Germany focuses on raw material and natural resource use, UK, Denmark, Switzerland and Portugal apply the concept in waste management. Finally, in China, more than a hundred of eco-city projects have been reported to take place in China (Ghisellini et al., 2016), an effect that can be directly attributed at the top-down approach that the Chinese government is applying by means of a national political strategy (Lieder & Rashid, 2016). Most of these circular pilot project cities have met or exceeded the targets set: for instance, Beijing has achieved a 62% reduction in energy consumption per GDP in 2010, a 45% increase in the rate of treated wastewater recycling, and a 45% reduction in consumption per capita from 2005 (World Economic Forum, 2014).

Despite the increasing adoption of CE worldwide, meta-analyses show that there still exist some research gaps that need to be filled. Firstly, Elia et al., (2016) found an imbalance of CE development through its different level of application: the most analysed field of intervention is currently the macro level (56% of analysed studies approached the assessment at this level) while 25% and 19% look at the meso and micro level respectively. The specific research gaps for each level were found to be a)the study of the effect of CE business and consumption models (refurbishing, leasing, remanufacturing) as a pendant issue at the micro-level (Ghisellini et al., 2016) with a preferable focus on the benefits that companies can get from its implementation, to stimulate more bottom-up adoption (Ghisellini et al., 2016; Lieder & Rashid, 2016); b) the development of assessment tools for the environmental performance of industrial symbiosis designs at the meso-level; and c) evaluation of projects and legislation implemented at the macro-level to track to provide feedback information to policy makers (Ghisellini et al., 2016). Critical research gaps observed in the study of Winans et al., 2017 also mention the CE concept application to and assessment of the biological systems and plastic flows. Finally, many authors also agree about the existence of a deep research on CE assessment and circularity indicators (Elia et al., 2016)

4.2. Principles of a Circular Economy of household biogenic waste in Amsterdam

To conceptualise circularity according to the objectives of this study, four main sources are used. The general concept will be presented according to the reports published by the leading organisation on CE, the EMF. Such institution works in partnership with business consultants such as McKinsey and fosters the potential of the circular economy for EU economies, by publishing series of consultancy reports (Gregson et al., 2015). The conceptualisation of the CE will be further contextualised at the European level including insights from a recent publication by the European Environmental Agency (EEA). The bureau is aligned with the European Commission strategy *"Closing the loop – An EU action plan for the circular economy"* and thus, publishes reports that aim at providing answers to some questions to bridge remaining knowledge gaps. To further position the concept within the Amsterdam context, some insights will be included from the Government-wide Programme for a Circular Economy released by the Dutch ministries of Economic Affairs and Infrastructure and the Environment. Finally, the vision of a circular Amsterdam will be added by including remarks from the reports jointly published by the Municipality of Amsterdam, The Netherlands Organisation for Applied Scientific Research (TNO) and the consultancy group Circle Economy.

4.2.1. Ellen MacArthur principles

According to the EMF, organic waste from food is a relevant segment in the category of short-lived products and consumables as it holds significant economic potential in being reintroduced into the biosphere after remaining energy and nutrients have been extracted. It acknowledges that biological nutrients are mostly discarded as sewage through centralised sewage systems or by means of the organic fraction in the municipal and industrial solid waste streams (Figure 6).

- A cascading scheme is proposed to optimise the value extraction of this stream. It starts by the extraction of biochemical feedstocks for being compounds with higher economic value and holding potential for fossil fuel derivatives replacement. This can be done by means of bio-refinery processes in which biomass is turned into a full range of fibres, sugars, and proteins thanks to the activity of microorganisms and enzymes. These by-products are the building blocks of plastics, medicines, and fuels and since its prices are usually higher than biofuels, and they will likely compete successfully with the latter in the future (Ellen MacArthur Foundation, 2013).

- The outcoming flow consists on the extraction of nutrients and soil improvers'. The alternative nutrients that organic flows such as sewage sludge, animal waste and food waste provide, would also be sufficient to cover the needs for fertiliser and break the dependence on minerals, but the successful implementation requires technological innovation and changes in the legislative frameworks.

- Finally, the remaining flow could be used as feed for energy by means of anaerobic digestion or other incineration.

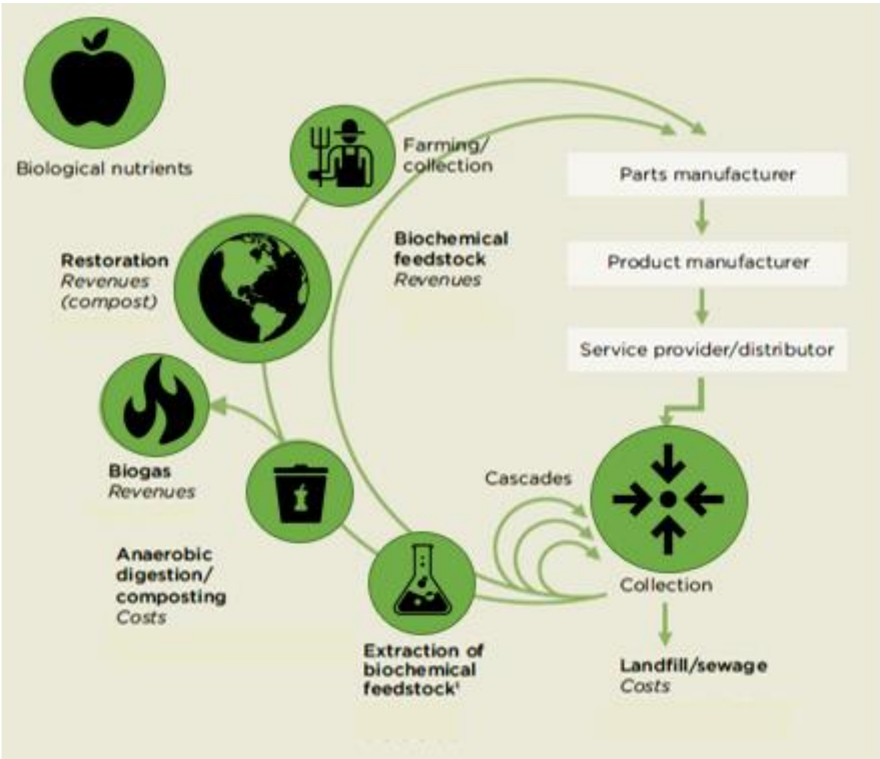

Figure 6. Overview of a CE of organic waste. Source: Adapted from EMF.

4.2.2. European Environmental Agency principles

The EEA used the EMF vision to base their conceptualisation of the key characteristics of a CE and took it a step further so that it could be used as a baseline for policy formulation. In the report *"Circular economy in Europe. Developing the knowledge base"*, the key characteristics of a CE are summarised as follows:

- Less input and use of natural resources: minimised and optimised exploitation of raw materials while delivering more value from fewer materials, reduced import dependence on natural resources, efficient use of natural resources, minimised overall energy and water use
- Increased share of renewable and recyclable resources and energy: non-renewable resources replaced with renewable ones within sustainable levels of supply, increased

share of recyclable and recycled materials that can replace the use of virgin materials, closure of material loops, sustainably sourced raw materials;

- Reduced emissions throughout full material cycle by using less raw material and sustainable sourcing, less pollution through clean material cycles;
- Fewer material losses/residuals: incineration and landfill limited to a minimum, dissipative losses of valuable resources minimised;
- Keeping the value of products, components and materials in the economy: extended product lifetime keeping the value of products in use, reuse of components, value of materials preserved in the economy through high-quality recycling.

4.2.3. Dutch government principles

According to the Government-wide Programme for a Circular Economy the main motivations from the Dutch government to implement a CE are to ease the increasing demand for raw materials, to limit the dependency of Netherlands on other countries in terms of access to raw materials and the climate change risks due to the considerable contribution of production chains to the consumption of energy and emissions of CO_2 (Government Netherlands, 2016).

- The preservation of natural capital is taken as a starting point, so that renewable instead of raw materials are used whenever possible. The extraction of primary raw materials, should be done in a sustainable manner;
- The bureau primes innovative processes since these create opportunities of exportation of goods and knowledge to existing businesses, start-up's, and for scientific institutions.
- Internationalisation is also regarded as an inherent aspect of the process because economies are becoming increasingly intertwined and the Dutch economy is regarded as highly dependent on foreign streams of raw materials;
- Cooperation is also seen as a must, so that public and private parties explore possibilities to implement technological social and system innovations from a shared vision and partnership. The targeted scale levels of cooperation are the national and international levels as well as local and regional, in which regional governments, companies and knowledge institutes jointly initiate endeavours;
- Digitalisation of the economy is crucial so that the design of a CE can benefit of higher accurate and efficient processes thanks to the intelligent infrastructure, energy networks, internet of things and social networks;
- Biological nutrients streams are regarded as a priority value chain;
- The optimum utilisation of biomass and food is envisioned to be achieved by sustainable consumption, in which consumer behaviour play a key role in the pursuit of it. Knowledge of consumer behaviour, education and culture are equally important as, if not more than, technological innovation;
- Organic residues resulting from production processes (loss of pre-consumption materials) should be recovered within the value chains and be turned into animal feed when they are not appropriate for human consumption;
- The nutrient cycle needs to be balanced by optimising the recovery of nutrients that are potentially scarce (phosphate, nitrogen, micro-nutrients) An enormous potential is acknowledged for the recovery of these nutrients from residues such as manure, waste water and purification sludge and can create room to produce artificial and organic fertilisers, soil improvers and growth media;

- The bureau also identified the need to optimise the applicability of cascading to reuse biotic products but makes an emphasis on not compromising the achievement of renewable energy targets, partially achieved thanks to the combustion of biomass. Finally, the green chemistry sector is likely to receive substantial economic support to processes such as sugar chemistry, timber refinery and pyrolysis.

4.2.4. Municipality of Amsterdam principles

The Amsterdam municipality envisioned a high-value recycling scenario of organic streams within the metropolitan area. The city regards shifting to circularity as an opportunity to improve inhabitants' quality of life, the creation of new jobs and business models. The municipality committed to reach an efficient recovery of natural resources and materials and stimulate economic activity, research and innovation:

- The design included aspects such as easy access to local food sources by, for instance, implementing urban agriculture strategies;
- The city is depicted as a future biorefinery hub that processes organic residual streams that can no longer be reused in a high-value manner;
- Cascading is regarded as a key process by which value can be recovered from organic streams, even though it is needed to upscale existing initiatives so that the volumes are greater and thus, economically beneficial;
- The use of bio-based materials appears as an alternative to reduce the impact of scarce building materials;
- The quality and the purity of a complex material stream such as the domestic organic waste is aimed at being improved by means of the implementation of street smart containers and smart reverse logistics solutions;
- Production of high-quality protein from organic waste and growing biomass in public spaces are opportunities to source organic local raw materials;
- Finally, fertilizer manufacturing and decentralized processing of sewage is regarded as an opportunity.

4.3. Development of a Table of criteria

4.3.1. Results from the literature reviews

As seen, the designs from the EMF are essentially technical, presenting strategies to recover and create value from organic streams. Apart from building a knowledge base, the foundation works on bringing together different stakeholders involved in production chains, from policy-makers, big industry players and consumers, which might have opposite interests. Hence, it avoids any normative nuances in its proposals. The EEA presents its own action framework but does not make special emphasis on the strategies intended to organic waste management. On the contrary, both the Dutch government and the municipality of Amsterdam see organic waste as a big opportunity. Both entities propose cascading as a model that would enable the creation and recovery of materials and value and both entities go further than a mere technical proposition but prime concepts such as cooperation, innovation, opportunity to export ideas and become a pioneer from which other regions can get inspiration. Also mention the engagement and learning of the society as an important asset. A synthesis of the items mentioned by each institution can be found in Table 2.

Table 2. Characteristics of a Circular Economy as mentioned in the different reports

CHARACTERISTICS OF A CIRCULAR ECONOMY	EMF	EEA	NL	AMS
Use of renewable energy sources	x	x	x	x
Design for re-use (disassembly, refurbishment…)	x	x		x
Design for resilience (modularity, versatility, adaptability…)	x	x		x
Composting of biological nutrients	x			
High-quality use of biomass waste (cascading)	x	x	x	x
Societal engagement			x	x
Cooperation among production chains' actors	x		x	x
Reducing the extraction of raw materials				
Reducing the amount of imported raw materials		x	x	
Reducing GHG emissions along the product's life cycle		x		
Reducing water and energy use in production	x	x		
Sustainable sourcing of raw materials		x	x	
Avoiding incineration or landfill by keeping materials inside the loop	x	x	x	x
Extending products' life	x	x		
High-quality recycling of technological nutrients	x	x		x
Replacing fossil fuels by sustainably produced biomass	x		x	x
Cooperation: exportation of knowledge and expertise			x	
Increasing efficiency through digitalisation			x	
Generation of economic value			x	x
Innovative business models			x	x
Innovative technological processes			x	x
Positive contribution to ecosystems				x
Avoidance of direct landfilling	x	x	x	x
Avoidance of direct incineration	x	x		
Provision of energy by means of combustion of biomass	x	x	x	x
Cascading (extraction of fine chemicals and by-products)	x	x	x	x
Preservation of local agricultural soil quality (recovery of soil improvers)	x	x	x	x
Urban agriculture	x		x	x
Consumer engagement and education	x	x	x	x
Employment generation		x	x	x
Use of digitalisation			x	x
Reverse logistics			x	x
Scarce nutrients recovery	x	x	x	x

4.3.2. Refinement and additions from the interviews with experts

From all the items presented in the Table 2 from the previous section, a preliminary Table of criteria was elaborated by including the most important aspects based on the amount of times they were mentioned in the reports. The preliminary table of criteria can be found in the Appendix (Table 1.1)

One of the aspects that was assessed in the interviews with experts was the relative importance of each criteria. The economic-related criteria were seen in most of the cases as a priority in the performance of technological innovations given that economic viability is a huge determinant of the eventual implementation of a solution. Environmental impact, need of natural resources as inputs for the processes and the extent to which material loops were closed was the second priority in most of the cases. Lastly, societal dimension, local benefits and innovation or international outlook were regarded as less priority in most of the cases.

The overall impression of the experts about the preliminary Table of criteria was quite positive, but also added different remarks. A first criterion was included referring to the chemical intensity of the process due to the generally high environmental impact that production of chemicals implies, extending the environmental performance of the process to a higher level. One of the interviewers also introduced a very interesting concept which he named "world impact", a criterion referring to the extent to which the process could help people living at the border for human ecosystems. His vision proposed considering other development scenarios different from the northern European, and how the innovative technology could benefit low and lower-middle income countries. This was not included in the final assessment due to the complexity of measurement but it is certainly worth to mention. Other criteria mentioned in the interviews were "health risks" and "comfort" as societal aspects to consider. Since comfort and the extent to which habits are changed determines the appraisal of sustainable innovations by society it was also included, as well as the importance of avoiding additional health risks. The final Table of criteria used for the Performance matrix of the technologies is presented below. The scoring system is discussed in the next chapter

Table 3. Final table of criteria to assess a Circular Economy in Amsterdam

TOPIC	CRITERIA
Resource consumption	Net consumption of energy during the process
	Net consumption of fresh water during the process
	Net consumption of chemical use during the process
Environmental impact	Impact of (by-)products to environmental pressures
	Fossil fuel replacement of (by-)product(s)
	GHGs transport emissions
Closed loops	Material fraction recovery and cascading potential
	The process removes material from material cycles due to combustion
Innovation	The process is innovative
	Improvement of the sustainability of other business models
Local benefits	Expertise about the process is found in Amsterdam
	The consolidation of this process could make Amsterdam an inspiration for other municipalities
Cooperation	Interest of local industrial stakeholders in (by-) product(s)
	Potential for world impact, international cooperation, knowledge exchange
Economy	Potential exportation of (by-)product(s) to other countries
	Economic value of the (by-)product(s)
	Economical sustainability
	Digitalisation and traceability of the local economy
Resilience	Demand of the process for local raw materials
	Demand of the process for imported materials
Society	Societal learning and engagement
	Risks for public health
	Change in the habits of society

4.4. Review of methods for measuring Circular Economy designs

This section presents the results of a literature review about indicators commonly applied to assess the sustainability of CE designs. Even though none of these methods were applied in the current study, it is interesting to include them as an overview of existing options with focus on the weaknesses they present. The purpose of presenting this is therefore to provide the reader with a set of possible solutions for the generalised lack of methods for assessing CE and the main obstacles to overcome in each option.

- Life-cycle Assessment A relevant family of circularity indicators are the ones following the principles of Life-Cycle Assessment (LCA). The LCA is a well-known multiple indicator method, traditionally applied at the macro-, meso- and micro- levels of CE (Elia et al., 2016). LCA is based on the development of a model that aims at describing the system under examination from the extraction of raw materials through processing, production, use and disposal of waste (Angelakoglou & Gaidajis, 2015). It has been standardized by international guidelines defined in the ISO 14040 family (Elia et al., 2016). Even though it has been widely used in industry, an important weakness of LCA is the tremendous amount of data involved, the limited availability of it plus the high demand of time and resources that the study requires (Cucek, Klemes, & Kravanja, 2012). Many authors point out that the approach is limited to environmental impacts, and thus, it is sometimes extended to include other dimensions, such as the economic or even the social (Angelakoglou & Gaidajis, 2015; Patrício et al., 2015). The fact that the communication of its results often asks for an expert audience makes the approach less attractive as a communication tool (Elia et al., 2016) and its lack of systematic method for generating and identifying sustainable solutions (Cucek et al., 2012).

- Material Flow Analysis It is frequent that authors adopt Material Flow Analysis (MFA) or derived indicators to measure the adoption of CE paradigm at the national, regional and city level (Elia et al., 2016). The MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Helmut, 2011) and allows researchers to monitor the flow of materials throughout their entire life cycle within a urban system (Zhang, 2013). It has been widely used as an environmental accounting approach in the field of industrial ecology (Moriguchi, 2007) and also urban metabolism (Voskamp et al., 2016; Zhang, Yang, & Yu, 2015). Nevertheless, some weaknesses have been pointed out with regards to the application of this method. Firstly, MFA studies lack of a unified methodology, which makes them in practice not really comparable and reliable (Rosado, Niza, & Ferrão, 2014). A second crucial drawback of this quantitative approach is a general lack of reliable data needed to perform these studies (Rosado et al., 2014) that it might hide upstream flows related to imports, production and exports of raw materials and products. Accordingly, they suggest that combining MFA with LCA would allow to weight mass flows with their environmental impacts to correctly identify those products and materials that ought to be the focus for reduction, substitution and more effective use.

- Substance Flow Analysis A similar indicator is the Substance Flow Analysis (SFA), which is used to address more specific questions such as like water, air or soil contamination by a single substance to understand the role that cities play in global biogeochemistry (Barles, 2010). SFA and MFA are related concepts, but use different methodologies: while MFA investigates the quantity and state of cross-sectional data at different life-cycle stages, SFA uses the Euler's and the LaGrange's method from hydromechanics to trace the path followed by a particle and observes the changes in the substance flows among different life-cycle stages (Zhang et al., 2015).

- Energy Accounting methods This family o of quantitative indicators developed to describe and analyse the material and energy flows at the macro level has been the description of urban metabolism in terms of solar energy equivalents, known as 'emergy' (Voskamp et al., 2016). One particularly interesting aspect of these analyses is that they account for the flows of materials and energy in different forms by quantifying the embodied energy. The approach has been applied successfully for Taipei, Beijing, Rome, and Xiamen (Zhang et al., 2015). A similar indicator is known as 'exergy', or the amount of useful work that can be performed by the energy contained in a system (Zhang, 2013). An advantage of emergy and exergy accounting is that both approaches allow researchers make flows of materials with different units of measurement comparable (e.g., masses or volumes of physical materials, the energy content of fuels, flows of money and information) to produce an integrated analysis that accounts for all flows (Zhang, 2013).

- Ecological Footprint The Ecological Footprint (EF) is a single-based index that estimates the biological capacity of the planet consumed by a specific human activity or population (Elia et al., 2016). EF is based in the assumption that many material and energy flows can be converted into land-area equivalents. Thus, the EF of a specified urban area is the biologically productive area of natural land required to produce the resources consumed, and to assimilate the wastes generated (C. Kennedy, Pincetl, & Bunje, 2011). The Ecological Footprint Standards stablishes the standardized methodology for the approach and was published by the Global Footprint Network (Elia et al., 2016). One of the main strengths of the EF concept is that it is attractive and intuitive, and that its methodology is continuously improved (Cucek et al., 2012) and thus, it can be used to easily communicate quantitative results obtained at the macro, meso and micro level. (Elia et al., 2016). EF originated similar approaches such as the MIPS (Material-Input-Per-Service) or the EcoindexTM (Singh, Murty, Gupta, & Dikshit, 2009).

- Sustainability of technology assessment In the study carried out by Dewulf & Van Langenhove, a set of five universal environmental sustainability indicators for the assessment of technology are presented. They are based in industrial ecology principles and their purpose is to assess the environmental but also the social and economic concerns. In this case, the indicators are referred to exergy terms. The thermodynamic basis guarantees analytical soundness in technical and scientific terms (Dewulf & Van Langenhove, 2005) and makes that the items measurable.

- Urban Harvest Approach Following a similar line of thought, the indicators intended to measure circularity within the Urban Harvest Approach were also worth to consider. Agudelo-Vera et al., developed the so called "Urban Metabolic Profile". This framework included four different indicators (Appendix Table 2.2.) and was applied to water cycles and organic waste streams (Leusbrock et al., 2015). Interestingly, those indicators were also applied by

Wielemaker, Weijma, & Zeeman to assess the match between the supply of organic nutrients (nitrogen, phosphorous, organic matter) by means of the application of new sanitation systems and the demand of urban agriculture systems.

- Metabolic efficiency indicators Many groups are also developing interesting indicator frameworks based on urban metabolism. The study from Villarroel Walker, Beck, Hall, Dawson, & Heidrich carries out a Multi-sectoral Systems Analysis, a framework built upon three components 1. Substance Flow Analysis 2. Metabolic Performance Metrics 3. Regionalized Sensitivity Analysis. The purpose of this metrics is to gauge the extent to which flows are moving in closed loops around the city ((Villarroel Walker et al., 2014) In the study by Rosado, Kalmykova, & Patrício (2016) a framework to identify urban metabolism characteristics based on the urban MFA indicators is presented, following the UMAn model developed based on the Economy Wide MFA principles. The MFA indicators considered are Direct Material Input (DMI), Imports (Imp), Exports (Exp), Domestic Extraction (DE), Domestic Material Consumption (DMC), Net Addition to Stock (NAS), Industrial Production (IP), Domestic Processed Output (DPO), and Recovery. Of interest was the Urban Metabolism Efficiency, which is assessed by accounting the share of different types of recovery solutions (recycling energy and biological treatment) to the DMC indicator.

5. PERFORMANCE MATRIX

This chapter contains the results of applying the Performance matrix. Section 5.1 provides an overview of the performance matrix, and conclusions from micro-, meso- and macro- levels are found in the sub-sections 5.1.1., 5.1.2., 5.1.3. respectively. Additionally, section 5.2 contains a summary of the main discussed topics in the interviews.

5.1. Overview of the Performance Matrix

As seen, the scoring processes has consisted in the attribution of a colour in a range of five depending to the extent to which the technology satisfied the optimal performance. The full Performance matrix is displayed in Figure 7. The Performance matrixes for each of the scales are displayed in each of the following sections.

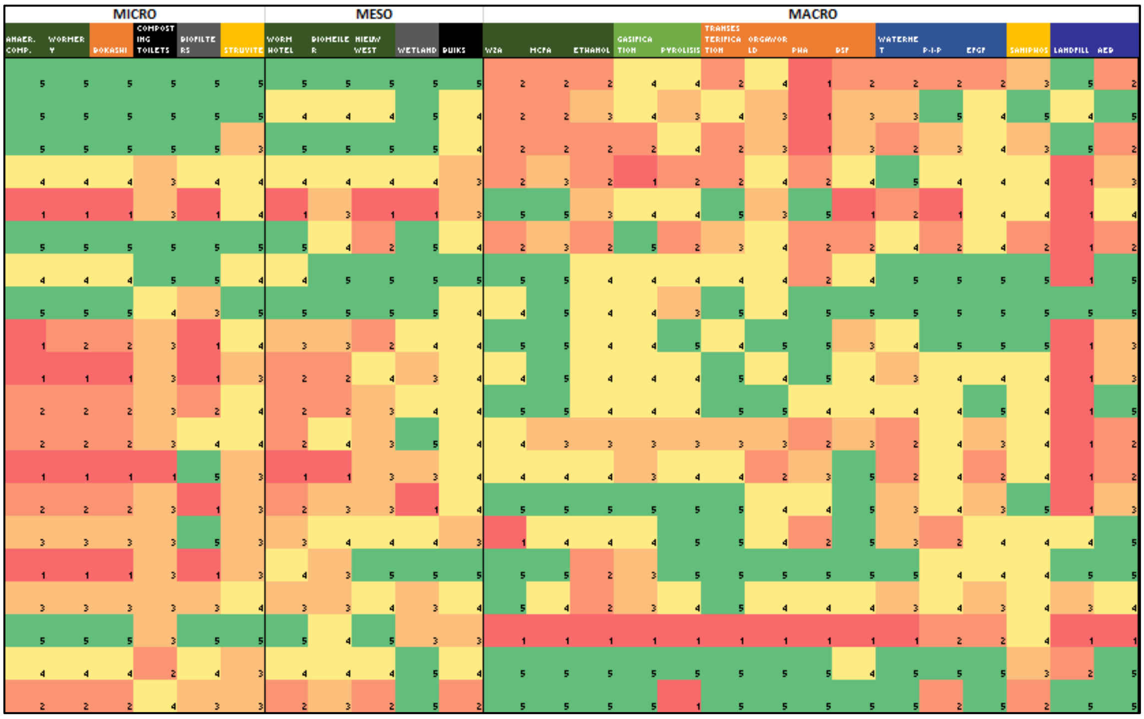

Figure 7. Full view of the Performance matrix

5.1.1. Micro-scale approach

As seen in Figure 8. the micro-scale technologies displayed a high environmental performance: technologies are relatively low-tech and mimic processes that take place in the nature so they are relatively simple and are not water nor energy nor chemical intensive. The products obtained have the potential to restore ecosystems (nutrient-rich compost, release of fresh water...) or are products that avoid the exploitation of finite resources (energy carriers such as biogas or struvite avoiding the depletion of phosphorous rock). Due to its small-scale functioning, additional GHG emissions due to transport are avoided. They also display high economic performance because technologies are simple, affordable and already in the market, so no significant investments are required. Costs concerning energy, water and chemical inputs are also avoided. Moreover, high material recovery rates are obtained, except for the anaerobic digestion at a building scale since the main product is an energy carrier. The recovery rates for struvite precipitation are remarkably high. In the case of composting-related processes all materials are captured in the outcoming compost stream since CO_2 production and material loss due to temperature dissipation are negligible. Small-scale approaches imply a high potential for community involvement. This requires societal education and awareness, which is regarded as an additional value by the Amsterdam municipality and the Dutch government.

One of the major weak points of micro-scale technologies is that they present a mismatch with Amsterdam's urban characteristics. As seen, Amsterdam's amount of high rise homes accounts for the majority, meaning that there is a very limited space for biogenic streams separation. The variety of products that the technologies provide is narrow and present a low economic appeal because products such as compost present a relatively low or inexistent market value in the Netherlands (Brolsma & Leeuwen, 2016). Moreover, even these products have the potential to restore soil eroded ecosystems, it should be important to assess if the potential for ecosystem's recovery would match the ecosystem pressures of the Amsterdam region. Even though shifting to small-scale circularity would be innovative per se given the current centralised sanitation scenarios, technologies are not innovative. An additional mismatch lays on the fact that small scale technologies are opaque processes: since circularity takes place within the boundaries of private spaces, the recovery rate for nutrients would be difficult to quantify, mismatching with the Dutch projects to establish a traceable and digitalised economy (Government Netherlands, 2016). Finally, even though the environmental benefits are significant, the technologies would be adopted by the citizens themselves, which would need an important replication process driven by a strong commitment from the Amsterdam citizens' side. Small-scale approaches require a shift to less-comfort behaviour from the side of citizens which might eventually hamper the wide adoption of micro-scale technologies. The approach requires of a highly educated and conscious society, which might imply and enforcement of educational campaigns by the municipality to bring this scenario into reality. The lack of economies of scale makes the process less attractive and that prevents industrial stakeholders get involved too. Biogenic wastes are highly putrescible and thus attract other living organisms that might imply a risk for human health. This aspect, together with other side effects such as odours, discomfort etc need to be controlled so that a micro-scale scenario for circularity becomes successful. Long term health effects of using urine-derived struvite need to be checked

Following the line of thought of the indicator "world impact", decentralised, small scale systems might match different contexts. Identifying areas with a low performance of large-scale infrastructures in which the weaknesses that these technologies present in Amsterdam are not major drawbacks has the potential to provide circular solutions to other regions that might avoid unsustainable, linear developments. Another strategy to foster small-scale processes might be by means of urban agriculture, which could benefit from the local production of compost.

The interviews revealed that some highly efficient processes such as anaerobic digestion are not spread at such a low level due to the high maintenance requirements in comparison to the processed volumes. It was also said that if smaller-scale techniques were capable to collect the biogenic flows in a neater, more concentrated way, they would potentially be more efficient than large scale treatments.

MICRO- SCALE PERFORMANCE	Aerobic composting bin	Domestic wormery	Bokashi bin	Composting toilets	Low-tech biofilters	Small-scale struvite precipitation
Net consumption of energy during the process	5	5	5	5	5	5
Net consumption of fresh water during the process	5	5	5	5	5	5
Net chemical use during the process	5	5	5	5	5	3
Impact of (by-)products to environmental pressures	4	4	4	3	4	4
Fossil fuel replacement of (by-)product(s)	1	1	1	3	1	4
GHGs transport emissions	5	5	5	5	5	5
Material fraction recovery and cascading potential	4	4	4	5	5	4
The process removes material from material cycles due to combustion	5	5	5	4	3	5
The process is innovative	1	2	2	3	1	4
Improvement of the sustainability of other business models	1	1	1	3	1	3
Interest of (by-)product(s) to local stakeholders	2	2	2	3	2	4
World impact, international cooperation, knowledge exchange	2	2	2	3	4	4
Potential exportation of (by-)product(s) to other countries	1	1	1	1	5	3
Economic value of the (by-)product(s)	2	2	2	3	1	3
Economical sustainability	3	3	3	3	5	3
Digitalisation and traceability of the local economy	1	1	1	3	1	3
Demand of the process for local raw materials	3	3	3	3	3	4
Societal learning and engagement	5	5	5	3	5	5
Risks for public health	4	4	4	2	4	3
Change in the habits of society	2	2	2	4	3	3

Figure 8. Performance matrix for small-scale technologies

5.1.2. Meso-scale approach

As it can be seen in Figure 9, meso-scale approaches display middle to high environmental performance. The processes are more engineered compared to micro-scale and thus require of a higher input in terms of energy, chemicals, water use. Nevertheless, similarly to micro-scale processes, the fact that they mimic spontaneous processes occurring in the nature makes them environmentally efficient. Same as in the micro-scale technologies, the products range is low but have the potential to restore ecosystems and replace finite resources, especially because renewable energy carriers are obtained. One of the advantages that this scale displays lays on the fact that it is traceable: since technologies are implemented outside from the private boundaries of citizens and managed by higher entities, that makes this approach more traceable and able of be aligned with the prospected digitalisation of the Dutch economy. The fact that larger amounts of materials are managed makes the processes attractive to local industrial partners. This can stimulate the design of more sustainable business models and outcoming streams can undergo more high-tech processes such as cascading. Even though the materials have a relatively low value, the initial economic investments in infrastructure terms are greatly recovered because of energy savings in the mid-term. The process applied at this scale pose an added value in terms of innovation, because new and more efficient technologies are created for existing markets. An additional advantage lays on the fact that implementing these technologies is not detrimental to the comfort of users: even though vacuum toilets have been largely criticised, the functioning of these technologies is not dependant on user's commitment to it. Even the required low commitment by citizens to the functioning of these technologies might imply a missed opportunity for citizen education and engagement, it is also important to point out at the potential for high skill training and job creation intended to the maintenance of the high-tech decentralised infrastructure. Finally, this type of approach also seems appropriate in the case of Amsterdam in the sense that the space limitation of households would not hinder its implementation.

A disadvantage of the meso-scale approach which is important to take in consideration is that sanitation installations (pipes, conduits…) would need to be rebuilt. The interviews revealed that the administrative processes required and the high economic costs are regarded as the main barriers to develop a meso-scale circularity of household biogenic waste. The economic value of the products obtained in all cases is still relatively low and is probably not interesting to local stakeholders. Despite the initial investments, there is evidence that the economic return of building decentralised systems to a meso-level occurs in the mid-term, which makes of it an interesting approach to apply in restauration and new urbanisation projects given the highly environmental and economic performance of these systems. Even though the recovery of materials and energy is currently more effectively done at this approach, possible environmental rebound effects new infrastructure and logistics need to be assessed before wider implementation.

In the interviews many experts highlighted the fact that meso- scale approaches (neighbourhood, district) were the most efficient since they provided economies of scale and were very efficient. The fact that the recovered materials have a low economic value and low local application, this approach might lead to a CE of household biogenic waste too focused on energy recovery, while material recovery should always be a priority to keep the materials running in cycles in the systems. Some interviewees made emphasis on the educational aspect and job employment potential of this approach, mentioning the value of highly skilled training that the maintenance of such systems requires, having a potential of professional education.

MESO- SCALE PERFORMANCE	Worm containers & hotels	Biomeiler	Nieuw West	Constructed wetland	Buiksloterham system
Net consumption of energy during the process	5	5	5	5	5
Net consumption of fresh water during the process	4	4	4	5	4
Net chemical use during the process	5	5	5	5	4
Impact of (by-)products to environmental pressures	4	4	4	4	3
Fossil fuel replacement of (by-)product(s)	1	3	1	1	3
GHGs transport emissions	5	4	2	5	4
Material fraction recovery and cascading potential	4	5	5	5	5
The process removes material from material cycles due to combustion	5	5	5	5	4
The process is innovative	3	3	2	4	4
Improvement of the sustainability of other business models	2	2	4	3	4
Interest of (by-)product(s) to local stakeholders	2	2	3	4	4
World impact, international cooperation, knowledge exchange	2	4	3	5	4
Potential exportation of (by-)product(s) to other countries	1	1	3	3	4
Economic value of the (by-)product(s)	2	3	3	1	4
Economical sustainability	3	4	4	4	3
Digitalisation and traceability of the local economy	4	3	5	5	5
Demand of the process for local raw materials	3	3	4	3	4
Societal learning and engagement	5	4	5	3	3
Risks for public health	4	4	4	5	4
Change in the habits of society	2	3	2	5	2

Figure 9. Performance matrix for meso-scale technologies

5.1.3. Macro-scale approach

As seen in Figure 10, one of the main strengths of large-scale, high tech approaches is the potential for upcycling. This lays on the fact that high value products are obtained from a residual stream, thus avoiding natural resources' use while generating economic value. Both currently applied large scale infrastructure and high-tech processes are not dependant on user behaviour and its efficiency is not limited by a lack of convenience. There is a broad range of innovative processes able to be applied at a large scale and the implementation of such projects implies the creation of highly skilled jobs. The fact that products are highly attractive for local industrial actors that might be also an incentive for spontaneous local collaboration and partnerships. This approach is compatible with the future digitalisation of the economy since materials are managed outside of private spaces so information is accessible and reliable.

Despite these advantages, they imply a relatively high energy, water and chemical use and the overall environmental benefits are uncertain in many cases. There is no opportunity for citizen participation in this process and this might encourage individuals to not act against environmental concerns. Many of the collected innovative technologies are still under development and pose severe constraints related to purity and appropriateness of residual streams as inputs for processes. Biogenic waste is highly putrescible and new, more efficient logistic systems would need to be applied to recover the valuable products that are in the streams before they are degraded. In that sense, the full potential of household biogenic waste can be easily reached if it is targeted at central infrastructure because there are economies of scale and the collection systems are already built.

Nevertheless, relying too much on the assumption that that only because the use of finite natural resources is avoided by cycling the waste stream can provide a fake indication that these processes have a necessary positive net environmental effect. As seen in the Performance matrix, a lot of energy, fresh water and chemicals are required to carry out high-tech process and environmental assessments considering the whole life cycle need to be done if rebound environmental effects are to be avoided.

Many interviewees mentioned that one of the problems that large-scale systems pose is that organic matter is too diluted in sewage sludge, and if it was more concentrated it would make recovery processes more economically efficient. Some interviewees suggested that a potential interesting approach could be to make use of large scale infrastructure and its economies of scale and "attach" material recovery and upcycling options in centralised processes and slowly going towards a smaller scale. Other opinions touched upon the fact that large-scale infrastructure presents advantages but also major drawbacks because facilities need a lot of maintenance and are very expensive. In general, all interviewees regarded positive a large-scale approach to circularity because it overcomes the barrier of adapting all households with separation at source infrastructure and the necessary commitment from Amsterdam citizens.

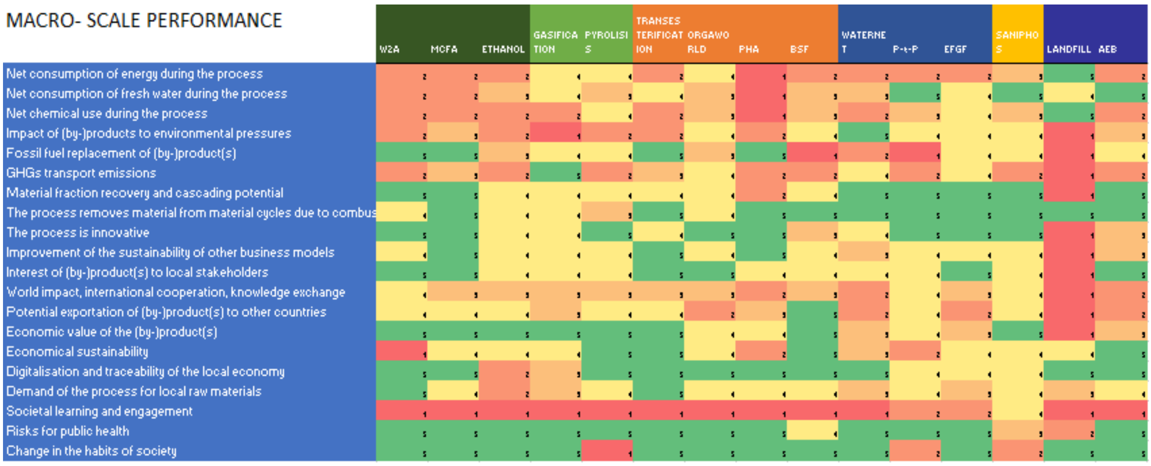

Figure 10. Perfomance matrix for marco-scale technologies

5.2. Additional results from the interviews

In general, all the interviewees acknowledged the relevance of CE and the increasing permeation of it within Dutch policy-making institutions. Among these, it was highlighted the paper that Dutch waterboards can play in pushing the shift towards a CE forward, since they have a broad vision of circular innovations in water management, the active stakeholders and ongoing projects and their perspective is not market oriented, so they can be crucial at connecting and accelerating projects. The role of Waternet was also regarded as important because it is pushing with more innovation and circularity to upgrade the traditional consideration of water treatment as a mere process to meet the requirements for discharging streams into the environment in a safe way.

Many interviewees commented that de-centralisation, small-scale processes based on the reuse of organic nutrients have been taken place on-site for some years, specially in agricultural activities. Only since a few years ago the debate was translated to urban areas discussions and framed within the sustainability discussions. Nevertheless, the main challenges of adding value to smaller-scale systems through biorefinery processes lay on the fact that these need economies of scale, which so far only occurs at the central, industrial level. The vision from some interviewees on the shift towards a CE is founded on a simultaneous bottom-up and top-down approaches, each of these depending on the material flow at hand. Additional barriers to implementing circularity are technologies' time to market and up-scaling of initiatives. Some other intrinsic problematic aspects of biogenic waste lays on the fact that it needs to be sanitized before its cycling.

All the experts provided insights about the potential of biorefinery and bio-based recovery solutions. The fact that central infrastructure is already built and it already provides economies of scale makes of it an important opportunity for the development of biorefinery options. Risks of unsustainability was an aspect at which most interviewees pointed out and recommended the enforcement of current environmental impact studies. A second crucial point of attention in this topic was the need for improve the separation of different biogenic waste subfraction to optimise the recovery of products. In this sense, the meso-scale sanitation systems implemented in Buiksloterham were remarked by some interviewees because it clearly depicts the advantages for further value recovery if the water content is removed from sewage sludge.

One interviewee pointed out that because of streams are more separated and its composition is better controlled, he saw more potential for biorefinery earlier in the food chain (pre-consumption phase) which would allow avoiding health risks and sanitation efforts. Because biogenic household waste is highly putrescible, one of the interviewees emphasised the importance of logistics to improve the temporal dimension of the material cycles. It was also suggested that the cascading model could still be optimised by extracting the different fractions in sequence so that the maximum mass and value are obtained from it. Finally, one interviewee regarded more positively to balance the nutrients cycles by the reintroducing them into the biosphere instead of implementing high-tech processes.

All interviewees expressed that there is currently no agreed upon method for assessing the environmental performance of technologies that enabled that recovery of biogenic nutrients. An interviewer mentioned that many studies in policy-making are based on the simultaneous application of an LCA and business case approaches. Other suggested frameworks were the use of the indicators provided by the European Commission. All interviewees expressed the difficulty of measuring circularity performances.

6. DISCUSSION

This chapter presents a reflection on the research methodology used to provide an answer to the research questions.

sRQ1- Which technological innovations at micro-, meso- and macro-scale can contribute to the circularity of household biogenic waste flows?

As explained in the Methodology chapter, this research sub-question has been addressed by means of literature review and interviews with experts. It was initiated from a given set of technologies from the report of Brolsma & Leeuwen (2016) because it scouted technologies with potential to recover biogenic materials from waste streams for an industrial park located in Duiven. Therefore, the initial set of technologies was already representative, plus it has undergone additions from both desk research and the five interviews with experts. This has minimized my condition of expat student, which might imply a lack of local knowledge about forthcoming projects and cutting-edge projects. Having the preliminary Inventory of technologies polished, completed and corrected by both practitioner and academic experts has added more value to the initial set. For this, even though the underpinning purpose of the Inventory of technologies was not to present a review of all possible existing technologies but to build a sample of alternatives to be scanned with the Performance matrix, the set of technologies becomes representative of the available possibilities in the Netherlands. Interestingly, way more technologies were found belonging to a macro-scale implementation. An explanation to that is that micro- and meso- scale technologies include mostly domestic infrastructure, whose development is limited by a lower market demand and lower economies of scale. On the contrary, macro-scale infrastructure included all kinds of industrial technologies and research and innovation processes which are more diverse because of the current interest of companies and academics to extract the maximum value from waste.

sRQ2- What are suitable criteria and indicators to determine the circularity of these technologies in Amsterdam?

The literature review to operationalise a CE of biogenic household waste in Amsterdam was based mainly in consulting and policy documents from four different institutions. For having a high-level focus, the writing style was less academic and sometimes there was room left for ambiguity or misspecifications. The literature review was self-made and this opens additional room for bias and possible omission of important aspects. The table that tracks the criteria mentioned by each institution (Table 2) provides transparency on the qualitative data gathering. The feedback from experts was very useful to reformulate high-level statements from policy documents and translate them into grounded cases. The interviews with experts played a significant role in providing completeness and avoiding redundancy to appraise circularity from many different angles.

sRQ3- How do these technologies perform on these circularity criteria and indicators?

All the technologies considered in the inventory were included in the Performance matrix. From the 23 criteria included in the Table of criteria (Table 3), only 20 were included due to feasibility of measurement. The process of scoring was self-made based on conclusions from literature review of technologies. Having a background in Biotechnology for my BSc. degree enables me to understand the principles and the functioning of different technologies, but a broader experience in the real-life applications of these technologies is necessary to judge its performance and put its advantages and drawbacks in a broader perspective. To bring transparency to the scoring process, a Scoring table (Appendix, section 3.1) was developed. Therefore, the possible arbitrariness of the colouring scale is avoided. The identification of patterns by visual identification is limited and not applicable to quantitative assessments but a useful system to evaluate criteria that would require a phase of indicator development and data gathering out of the cope of this MSc. thesis. The advantages of using a colour as a descriptive indicator is also an appropriate means of comparison in between diverse options and a system to assess qualitative and quantitative data simultaneously.

A working assumption has been that by aggregating several technologies according to their scale of operation it would provide information of performance at a scale level. A logic assumption that might flow from that is that the broader the sample of technologies, the clearer the patterns that can be identified within a similar scale. This was not the case if we compare the colouring patterns from the micro-scale (6 samples, Figure 8) to the macro-scale (15 samples, Figure 11). The categories at which each scale performs the better are clearer in the first case. An underlying factor affecting the pattern colours might be the flow at which each technology is operating. Adding a second level of classification related to the type of flow might improve the visual appearance.

Main RQ: How does the performance of innovative technologies implemented at the micro- meso- and macro- scales compare in terms of circularity?

The study is thus meaningful in many ways. The developed Performance matrix overcomes some of the limitations presented by most circularity assessments. It does not require of large data sets, it is able to compare numerous technologies simultaneously and is designed to measure circularity. It still requires of a lot of information, but it successfully organises it and systematically analyses it. Through the study of circular designs, I have also encountered the fact that many disciplines are combined in CE projects. While a 5-scale colouring system might seem a bit of a simple scoring method, it might help overcoming disciplinary boundaries in interdisciplinary debates. The underpinning value is that a Performance matrix might with a simple scoring system an appropriate method by means of which experts of diverse backgrounds can be involved and establish a dialog in a structured way.

One of the disadvantages of the developed method is that is not able to be directly applied in different contexts. The criteria are tailor-made and are a result of the envisioned circularity for a certain geographical area with certain available technologies, which might be different for another one. This follows a bit the line of the overall circular economy concept, which is more of an umbrella word that is adapted according to local situations more than a universal end.

7. CONCLUSIONS

7.1. Which technological innovations at micro-, meso- and macro- scales contribute to the circularity of household biogenic waste?

A total of 26 different technologies have been identified within the Amsterdam metropolitan area that are able to process and recover biological materials from household biogenic waste. There has been an unequal number of technologies applied at certain scales: 6 technologies implemented at the micro scale were found, 5 at the meso- and 15 at the macro-. This can be explained by the fact that the macro- scale accumulates volumes of biogenic waste that meet the demands of economies of scale that high-tech processes such as the ones based in bio-refinery require. An important observation was the fact that, the larger the scale of implementation, the larger the number of by-products that could be obtained from each technology. It was also notable the increasing degree of technologies complexity if the scale was increasing as well, to the point that the technologies became combinations of processes.

The important aspects in relation of the performance of these technologies that were raised during the interview were mainly three. Firstly, the separation at source of the different sub-fractions of household biogenic waste was an aspect that largely determines the feasibility and the efficiency of its implementation and an aspect to be improved. Because household biogenic waste takes place in a very homogeneous form in Amsterdam (the solid fractions are mostly discarded together with the residual waste and the liquid fraction is mixed with municipal sewage sludge) biological nutrients are very diluted and mixed and this maxes the material and the economic value of the different sub-fractions different to recover. When separation cannot take place at the point of generation due to urban constraints, it then needs to be addressed in the pre-treatment phases of large-scale technologies, which consists the limiting factor in many innovative developments. Secondly, biogenic flows are highly putrescible and a rapid and efficient waste logistics needs to be implemented before valuable compounds are degraded. In this sense, systems such as the smarts containers equipped with sensors that provide increased information on the composition of the waste and possibilities to match supply and demand might be of help (Circle Economy, 2015). Finally, a third important aspect for these technologies to function no matter the scale they were implemented is the fact that, because the composition of household domestic waste is highly unforeseeable and human excreta contains pathogens and heavy metals, dealing with these streams might imply health risks that should never be underestimated and approached very often with sanitation processes. This aspect large limits the different applications of the products obtained from cycling processes.

7.2. What are suitable criteria and indicators to determine the circularity of these technologies?

The literature reviews indicated the current lack of existing methods to evaluate Circular Economy designs, an aspect that was also confirmed through the interviews with experts. The main problems that current measurement tools pose are three: they are resource- (data, time, budget) intensive, they were designed for assessing linear processes and they are not appropriate for comparing different options. Nevertheless, some more recent methods such as the Urban

Harvest Approach or the Urban Metabolism indicators (Leusbrock et al., 2015) pave the path towards new assessment tools. It is important that a tool that overcomes or improve these limitations is eventually developed because it is often the case that sustainability and circularity assessments are omitted or substituted by assumptions that might lead to a wrong decision.

Circularity has been found to be an umbrella concept under which to frame technical designs. Nevertheless, it leaves room for the attachment of other social values, that highly depend on the area in which circularity designs are applied. This might explain the existing trend about developing different frameworks of indicators applied at the macro scale depending on the region. Similarly, the tool for measuring the circularity in this thesis has been the development of a table of 23 criteria considering the following topics: Resource consumption, Environmental impacts, Closed loops, Innovation, Local benefits, Cooperation, Economy, Resilience, Society. From the 23 criteria, 20 have been included in the assessment. The development of the assessment tool has ended at the point of developing criteria that are capable of being assessed qualitatively, but a necessary next step to make assessments more accurate would be to make these indicators measurable. Nevertheless, this is not a critical drawback related to the main purpose of this thesis because the objective was not to decide the best technological alternative but to identify common traits among three different scales of approach by aggregating a certain number of technologies.

7.3. How do these technologies perform on these circularity criteria and indicators?

This answered has been addressed by assessing the 26 technologies against the 20 criteria by using a Performance matrix and a colour rating system. This has been useful to identify strengths and weaknesses of the different scales of approach. Even though extended detail about the advantages and drawback of each scale can be found in Chapter 5, the following conclusions can be derived.

Small-scale approach is highly efficient in economic and environmental terms and implies a very interesting and necessary opportunity for citizens' education and engagement. At the same time poses significant drawbacks in relation to their capacity of matching the Amsterdam context. Starting by the fact that the urban characteristics of the city make its implementation unlikely given a lack of space, its benefits can only be obtained through replication, which means that a lot of people should engage to these technologies. This is difficult to happen given the lack of comfort and the profound behavioural change some systems require, which would challenge the Amsterdam citizen's environmental awareness and engagement. Creating the demand for these technologies could be useful in making them viral.

The meso-scale approach loses the potential for citizen education and engagement but maintains more comfort and better user experience. Important initial investments are required to rebuild facilities in a central way, but many cases of study report that the environmental and economic saving pay off in the mid-term. Even though seems to be the preferred option from institutions, a point for improvement in meso-scale approaches would be good to address. The current technologies offer a very limited set of by-products with quite a low economic interest and hence, not attractive to local stakeholders. This translates into the fact that current meso-scale approaches are focused on the energy recovery which, despite of being achieved very efficiently, is not the ideal option since it removes materials from cycles. To the view of this research, it would be of interest to study the capacity of small scale biorefineries to match the volumes dealt at the meso-level and enable the production of more attractive products to local stakeholders.

The macro-scale approach offers a wide range of possible products through complex and integrated processes. Moreover, the products are of higher economic value than lower scales. Two main advantages of this scale of approach are the already built central infrastructure, which avoids some costs, together with the economies of scale that it offers. That's why recovery and biorefinery processes can be patched to traditional processing plants to optimise the recovery of valuable materials. It has also been observed that a significant amount of large scale technologies is in an early stage of development. Nevertheless, it is important to notice that high-technological, large scale processes are often energy and chemical intensive. If the overall environmental result is positive only because the use of fossil fuels or finite resources is avoided might omit this aspect and led to unsustainable decisions. In this sense, the interviewees also emphasised on the need to enforce sustainability assessment studies.

Overall, it can be concluded that the Performance matrix developed in this research has been useful to streamline a systematic comparison among different scales of approach for the design of a circular economy of household biogenic waste. It has been an efficient way to summarize a large amount of insights and the 5-scale colouring method has been useful to depict emerging patterns at a larger level of aggregation among different scale. Main limitations of this tool lay on the fact that the criterial are not measurable, even though able to be assessed descriptively. This level of specificity might be already adequate in the context of CE discussions, were experts from multiple disciplines and opposite backgrounds take part on the decision-making.

List of references

Agudelo-Vera, C. M., Leduc, W. R. W. A., Mels, A. R., & Rijnaarts, H. H. M. (2012). Harvesting urban resources towards more resilient cities. *Resources, Conservation and Recycling*, *64*, 3–12. https://doi.org/10.1016/j.resconrec.2012.01.014

Amsterdam Smart City. (n.d.). The Green Living Lab. Retrieved October 22, 2017, from https://amsterdamsmartcity.com/projects/the-green-living-lab

Anand, C. K., & Apul, D. S. (2014). Composting toilets as a sustainable alternative to urban sanitation - A review. *Waste Management*, *34*(2), 329–343. https://doi.org/10.1016/j.wasman.2013.10.006

Angelakoglou, K., & Gaidajis, G. (2015). A review of methods contributing to the assessment of the environmental sustainability of industrial systems. *Journal of Cleaner Production*, *108*, 725–747. https://doi.org/10.1016/j.jclepro.2015.06.094

Barles, S. (2010). Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. *Journal of Environmental Planning and Management*, *53*(4), 439–455. https://doi.org/10.1080/09640561003703772

Biodiesel Amsterdam. (n.d.). Biodiesel. Retrieved from https://biodieselamsterdam.nl/het-proces/?lang=en

Brolsma, R., & Leeuwen, E. Van. (2016). Circular Solutions, 1–27.

Brunner, P. H., & Helmut, R. (2011). *Pratical Handbook of Matreial Flow Analysis*. *Complete Casting Handbook*. https://doi.org/10.1016/B978-1-85617-809-9.10003-9

Buurtcompost. (n.d.). Pilot Ondergronds Composteren. Retrieved October 22, 2017, from http://buurtcompost.nl/pilot-ondergronds-composteren/

Cargill. (n.d.). Alcohol/Ethanol. Retrieved from http://www.cargill.nl/en/products-services/alcohol-ethanol/index.jsp

CBS. (2017). Urban waste water treatment per province and river basin district.

Chen, X., Fujita, T., Ohnishi, S., Fujii, M., & Geng, Y. (2012). The Impact of Scale, Recycling Boundary, and Type of Waste on Symbiosis and Recycling: An Empirical Study of Japanese Eco-Towns. *Journal of Industrial Ecology*, *16*(1), 129–141. https://doi.org/10.1111/j.1530-9290.2011.00422.x

Circle Economy, C. of A. (2015). Circular Amsterdam: A vision and action agenda for the city and the metropolitan area.

Clean Tech Delta. (n.d.). Enerkem's project. Retrieved from http://www.cleantechdelta.nl/nieuws/waste-chemicals-coming-rotterdam

Cucek, L., Klemes, J. J., & Kravanja, Z. (2012). A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production*, *34*, 9–20. https://doi.org/10.1016/j.jclepro.2012.02.036

Department for Communities and Local Government. (2009). *Multi-criteria analysis: a manual*.

Dewulf, J., & Van Langenhove, H. (2005). Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment. *Resources, Conservation and Recycling*, *43*(4), 419–432. https://doi.org/10.1016/j.resconrec.2004.09.006

El-fadel, M., Findikakis, A. N., & Leckie, J. O. (1997). Environmental Impacts of Solid Waste Landfilling, (November 1995), 1–25.

Elia, V., Gnoni, M. G., & Tornese, F. (2016). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 1–11. https://doi.org/10.1016/j.jclepro.2016.10.196

Ellen MacArthur Foundation. (2013). Towards the Circular Economy.

Ellen MacArthur Foundation. (2015). Delivering the Circular Economy. A toolkit for policymakers.

Ellen MacArthur Foundation. (2017). Urban biocycles.

Energie- en Grondstoffenfabriek. (n.d.). Producten. Retrieved from https://www.efgf.nl/producten

Environment Australia. (2002). Biodegradable Plastics – Developments and Environmental Impacts, (3).

Gemeente Amsterdam. (2015). Afvalketen in Beeld.

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Government Netherlands. (2016). A Circular Economy in the Netherlands by 2050. Retrieved from https://www.government.nl/documents/policy-notes/2016/09/14/a-circular-economy-in-the-netherlands-by-2050

Gregson, N., Crang, M., Fuller, S., & Holmes, H. (2015). Interrogating the circular economy: the moral economy of resource recovery in the EU. *Economy and Society*, *44*(2), 218–243. https://doi.org/10.1080/03085147.2015.1013353

Grimm, N., Grove, J. M., Pickett, S. T. a, & Redman, C. L. (2008). Integrated Approaches to Long-Term Studies of Urban Ecological Systems. *Bioscience*, *50*(7), 571–584. https://doi.org/10.1641/0006-3568

Groen, B. J. (2016). Biorizon - The way to aromatics, (June), 66–68.

Grootscholten, T. I. M., Strik, D. P. B. T. B., Steinbusch, K. J. J., Buisman, C. J. N., & Hamelers, H. V. M. (2014). Two-stage medium chain fatty acid (MCFA) production from municipal solid waste and ethanol. *Applied Energy*, *116*, 223–229. https://doi.org/10.1016/j.apenergy.2013.11.061

Ivanov, V., Stabnikov, V., Ahmed, Z., Dobrenko, S., & Saliuk, A. (2014). Production and applications of crude polyhydroxyalkanoate-containing bioplastic from the organic fraction of municipal solid waste. *International Journal of Environmental Science and Technology*, *12*(2), 725–738. https://doi.org/10.1007/s13762-014-0505-3

Jonkhoff, E., Kalma, A., & Kooij, E. van der. (2012). Amsterdamse kringlopen in beeld, 48.

Kalmykova, Y., & Rosado, L. (2015). Urban Metabolism as Framework for Circular Economy Design for Cities. *Proceedings of the World Resources Forum 2015*, (October). Retrieved from http://publications.lib.chalmers.se/publication/232085-urban-metabolism-as-framework-for-circular-economy-design-for-cities

Kennedy, C. (2007). Urban metabolism. Retrieved from http://www.eoearth.org/view/article/156804/

Kennedy, C., Cuddihy, J., & Engel-yan, J. (2007). of Cities, *11*(2).

Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*, *159*(8–9), 1965–1973. https://doi.org/10.1016/j.envpol.2010.10.022

Kuntke, P. (n.d.). *Nutrient and energy recovery from urine*.

Le Compostier. (n.d.). Retrieved October 22, 2017, from https://amsterdamsmartcity.com/users/rowinsnijder

Lebersorger, S., & Schneider, F. (2011). Discussion on the methodology for determining food waste in household waste composition studies. *Waste Management*, *31*(9–10), 1924–1933. https://doi.org/10.1016/j.wasman.2011.05.023

Leusbrock, I., Nanninga, T. A., Lieberg, K., Agudelo-Vera, C. M., Keesman, K. J., Zeeman, G., & Rijnaarts, H. H. M. (2015). The urban harvest approach as framework and planning tool for improved water and resource cycles. *Water Science and Technology*, *72*(6), 998–1006. https://doi.org/10.2166/wst.2015.299

Lieder, M., & Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *Journal of Cleaner Production*, *115*, 36–51. https://doi.org/10.1016/j.jclepro.2015.12.042

Lohri, C. R., Diener, S., Zabaleta, I., Mertenat, A., & Zurbrügg, C. (2017a). Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings. *Reviews in Environmental Science and Bio/Technology*, 81–130. https://doi.org/10.1007/s11157-017-9422-5

Lohri, C. R., Diener, S., Zabaleta, I., Mertenat, A., & Zurbrügg, C. (2017b). Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings. *Reviews in Environmental Science and Bio/Technology*, 81–130. https://doi.org/10.1007/s11157-017-9422-5

Loorbach, D. A. (2010). Transition Management for Sustainable Development: A Prescriptive, Complexity-Based Governance Framework. *Governance, An International Journal of Policy, Administration, and Institutions.*, *23*(1), 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x

Mendoza, G., & Macoun, P. (1999). *Guidelines for Applying Multi-Criteria Analysis to the Assessment of Criteria and Indicators*. *Management*. https://doi.org/10.1016/j.ecolind.2006.11.006

Ministry of Internal Affairs. (2015). City Deal Circulaire Stad, 1–8.

Moriguchi, Y. (2007). Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles and Waste Management*, *9*(2), 112–120.

https://doi.org/10.1007/s10163-007-0182-0

Orgaworld. (n.d.). Amsterdam: Greenmills anaerobe vergistingsfabriek. Retrieved from http://orgaworld.nl/meer-over-ons-bedrijf/onze-locaties/amsterdam-greenmills

Patrício, J., Costa, I., & Niza, S. (2015). Urban material cycle closing - Assessment of industrial waste management in Lisbon region. *Journal of Cleaner Production*, *106*, 389–399. https://doi.org/10.1016/j.jclepro.2014.08.069

Power, T. K. I. P. (2015). TKI Project Power to Protein, (September).

Power to protein. (n.d.). The Power-to-Protein principle. Retrieved from https://www.powertoprotein.eu/about/

Protix. (n.d.). Ingredients. Retrieved from https://protix.eu/ingredients/

Roest, K., Smeets, P., van den Brand, T., Cortial, H., & Klaversma, E. (2016). TKI Loop-closure Cleantech Playground, (September).

Rosado, L., Kalmykova, Y., & Patrício, J. (2016). Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. *Journal of Cleaner Production*, *126*, 1–12. https://doi.org/10.1016/j.jclepro.2016.02.139

Rosado, L., Niza, S., & Ferrão, P. (2014). A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model. *Journal of Industrial Ecology*, *18*(1), 84–101. https://doi.org/10.1111/jiec.12083

Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development*, *17*, 48–56. https://doi.org/10.1016/j.envdev.2015.09.002

Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators*, *9*(2), 189–212. https://doi.org/10.1016/j.ecolind.2008.05.011

United Nations. (2016). The world's cities in 2016.

Villarroel Walker, R., Beck, M. B., Hall, J. W., Dawson, R. J., & Heidrich, O. (2014). The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, *141*, 104–115. https://doi.org/10.1016/j.jenvman.2014.01.054

Voskamp, I. M., Spiller, M., Stremke, S., Bregt, A. K., Vreugdenhil, C., & Rijnaarts, H. H. M. (2016). Space-time information analysis for resource-conscious urban planning and design: A stakeholder based identification of urban metabolism data gaps. *Resources, Conservation and Recycling*. https://doi.org/10.1016/j.resconrec.2016.08.026

Vymazal, J. (2010). Constructed Wetlands for Wastewater Treatment, 530–549. https://doi.org/10.3390/w2030530

Waternet. (n.d.). Nieuwe Sanitatie. Retrieved from https://www.waternet.nl/werkzaamheden/nieuwe-sanitatie/

Wielemaker, R. C., Weijma, J., & Zeeman, G. (2016). systems for reuse in Urban Agriculture. *"Resources, Conservation & Recycling."* https://doi.org/10.1016/j.resconrec.2016.09.015

Winans, K., Kendall, A., & Deng, H. (2017). The history and current applications of the circular economy concept. *Renewable and Sustainable Energy Reviews*, *68*(October 2015), 825–833. https://doi.org/10.1016/j.rser.2016.09.123

World Economic Forum. (2014). Towards the Circular Economy : Accelerating the scale-up across global supply chains, (January).

Yong Geng, Joseph Sarkis, Sergio Ulgiati, P. Z. (2013). Measuring China's Circular Economy.

Zeeman, G., Kujawa, K., de Mes, T., Hernandez, L., de Graaff, M., Abu-Ghunmi, L., … Lettinga, G. (2008). Anaerobic treatment as a core technology for energy, nutrients and water recovery from source-separated domestic waste(water). *Water Science and Technology*, *57*(8), 1207–1212. https://doi.org/10.2166/wst.2008.101

Zhang, Y. (2013). Urban metabolism: A review of research methodologies. *Environmental Pollution*, *178*, 463–473. https://doi.org/10.1016/j.envpol.2013.03.052

Zhang, Y., Yang, Z., & Yu, X. (2015). Urban Metabolism: A Review of Current Knowledge and Directions for Future Study. *Environmental Science and Technology*, *49*(19), 11247–11263. https://doi.org/10.1021/acs.est.5b03060

APPENDIXES

Appendix 1: Preliminary material provided to the interviewees

Table 1.1. Preliminary Table of criteria

Principles	Criteria
Energy and water use	Net consumption of energy during the process
	Net consumption of water during the process
Environmental impact	The (by-)product(s) obtained have the potential to restore ecosystems
	The process contributes to the incineration of waste
	Environmental impact (requires transport, use of toxic substances, increses emissions)
Closed loops	The process keeps a significant part of the material within a closed loops
	The process recovers a significant fraction of biological nutrients (C,N,P) in mass terms
Innovation	Innovativeness of the process
	The process can benefit from and/or stimulate digitalisation
	The process holds the potential to stimulate innovative business models
Local benefits	Potential expertise within the Amsterdam metropolitan region
	Amsterdam could become a sucessful case to inspire other municipalities
Cooperation	The (by-)product(s) are of interest to local stakeholders
	The process stimulates cooperation among industrial stakeholders in Amsterdam
	The process can benefit different market sectors in Amsterdam
	The process stimulates international cooperation and knowledge exchange
Economy	The expertise of the process can be exported to other countries
	The (by-)product(s) of the process are of economic value
	The process is economically beneficial
	The process holds potential for employment generation
Resilience	The process reduces the local demand for raw materials
	The process reduces the local demand for imported materials
Society	The process involves societal learning/engagement

Table 1.2. Preliminary Inventory of technologies handed to the interviewees

Input flow	Process	Technology	Description
Food	Anaerobic digestion	Composting bin (indoor)	Stable organic end-product (compost), other by-products such as leachate, CO_2 and H_2O vapour. Compost contributes to soil quality but has no economic value in the NL. Indoor composting bins take ten to fourteen days to convert the waste and the price for the whole kit oscillates around 50-70 €.
Food	Composting	Composting pile	Same process, with larger composting piles (250 l) usually carried out outdoors. Affected by climate conditions, 3-4 months 50-120 €.
Food	Anaerobic Digestion	Nieuw West GFT management/	3300 homes in Nieuw West (Amsterdam) separated (48% sep. rate) collected, processed by Orgaworld,

			obtention of compost (used public spaces) and biogas.
Food	Anaerobic Digestion	Greenmills cluster / Meerlanden	Orgaworld processes unpackaged supermarket food and organic waste separated in Amsterdam. Their capacity of digestion is 120.000 tons/year and the yearly outputs produced are 350.000 m3 of purified water, 5 MW of electric energy, 5.5 MW thermal energy and 3.500 tonnes of fertilizer. Meerlanden carries out a similar process.
Food*	Vermicomposting	Domestic wormery	Aerobic organic waste degradation and stabilization by interaction of microorganisms and earthworms under controlled conditions. 1-2% higher N content and way less heavy metals. Succeptibility of worms to waste composition (low toleration to meat, fish, dairy products, oil, high vinegar and salt concentrations. Less time consuming and more economically beneficial. 70 L indoor wormeries, 80-50 €.
Food*	Vermicomposting	Worm Hotels project (Le Compostier)	Wooden worm composting containers enable neighbours to compost their organic waste together in Amsterdam. Plant growth integrated in the device, plus the organisation offers workshops and informative sessions.
Food*	Vermicomposting	Underground composting project (Buurtcompost + Gemeente Amsterdam + Hogeschool van Amstedam)	GFT underground worm container. Emptied two times a year, compost takes place during all the seasons.
Food*	Vermicomposting	Protix Biosystems	Production of ingredients for animal nutrition based on insects grown in food waste (needs certification, household waste cannot be used).
GW	Biofiltering	Low- tech biofilters (De Ceuvel)	Implemented at office houseboats in De Ceuvel (Amsterdam). Low tech biofilters processed grey water consisting of two pallet tanks filled with a mixture of gravel and sand, topped up with reed. Achieved sufficient water quality for discharge into the ground based on Dutch regulation.
GW	Anaerobic digestion + Algae growth+ Biofiltering	Sandy and Helyo- filters (Nioo-Knaw building, developed by DeSah BV, Ingrepro and WUR)	System: Vaccum toilet → Fermenter (biogas obtention, energy system) → Alga cultivation system and helophyte filter (water purification). After purification the streams flow into a helophyte filter. Helophytes are aquatic plants such as reed and cattails. Purified water flows into a pond and

			the open ditches in the surrounding area. Another option is to pass water through the soil, pump it up and reuse it for flushing toilets. By harvesting the algae valuable minerals such as phosphates are recovered to be used as agricultural fertilizers By harvesting the algae valuable minerals such as phosphates are recovered to be used as agricultural fertilizers.
GW	Biofiltering	Urban constructed wetlands	Constructed wetlands (CWs) are engineered systems that take advantage of the natural processes involving wetland vegetation, soils, and the microbes to assist in wastewater treatment. Operation and maintenance costs are much lower compared to conventional treatment systems. In addition to treatment, constructed wetlands Provide other ecosystem services such as flood control, carbon sequestration or wildlife habitat.
TW	RWZI process	RWZI process (Waternet)	GW+ BW are directed via sewer conduits to central sewage treatment. Treatment steps a) Separation against particle size (grids, settlement tanks, grease and oil traps) b) Aerobic purification with activated sludge c) N removal, anoxic tank, P removal. Biogas that is released during sludge fermentation at the RWZI is also conveyed to the AEB for the generation of electricity and heat. 11 to 12 kilo tonnes of phosphor on an annual basis. The average scale of a Dutch sewer drain treatment facility (RWZI) in the Netherlands is 66.000 residents (Brolsma & Leeuwen, 2016) and Amsterdam's sewer drain water is purified in the plant located in the Western Harbour District.
TW	Aerobic composting	Composting toilet	Requires little or no use of water and it is not linked to the centralised wastewater treatment system. Consists of a toilet and a composting tank. Composting takes place aerobically. Use not recommended in the NL due to health risks and users discomfort.
TW	Struvite recovery	Urine-diverting toilet + Struvite precipitation (De Ceuvel)	Pure urine from a waterless urinal at Café De Ceuvel was stored in two 100 L buffer tanks. Nutrients were recovered from the urine using struvite ($MgNH_4PO_4.6H_2O$) precipitation and adsorbent materials (clinoptilolite zeolite and biochar) to generate fertilisers. Urine-derived struvite resulted an excellent fertilizer. Users seemed to accept these initiatives if the level of comfort is comparable to conventional systems.

TW	Composting	Composting toilet + neighbourhood based plant	Implemented in De Ceuvel, the citizens used an Urine-diverting toilets and brought the disposed faeces to a neighbourhood based plant, where anaerobic digestion took place out of which biogas and compost was produced.
Unsorted	Landfill	Landfill fields	Landfilling consists in the disposal of waste material by burial. The release of gas and leachate away from the landfill boundaries presents serious risks to the surrounding environment. Apart from health hazards, these concerns also include fires, explosions, vegetation damage, unpleasant odours, landfill settlement, ground water pollution, air pollution and gas emissions contributing to global warming. In the NL, there is a landfill ban since 1995 but exemptions can be granted if there is a temporary shortage of incineration capacity.
Unsorted	Combustion (Waste-to-Energy)	AEB	AEB receives 1.4 million tons of municipal and industrial waste annually. The Waste-to-Energy plant operated by AEB processes 850.000 tonnes of the municipal solid waste (MSW) and the Waste Fired Power Plant (WFPP) processes 530.000 tonnes of industrial waste. From the processes, 1 million MWh of electricity are produced annually, that feed 320.000 households with electricity. Heat is also produced: 600.000 gigajoule a year over the last years. This heat is used for district heating: hot water and central heating of Amsterdam households The high-value materials (both ferrous and non-ferrous metals) are recovered from the bottom ashes remaining after the incineration. Finally, the low-value bottom ash is used as filling material in road building or as a replacement for dredged sand in the ocean floors.
Lignocellulosic fractions	Gasification	Gasification expertise in the NL	Thermal treatment that converts dry biomass into syngas that can be used either as fuel (for example, to generate steam or electricity) or for the production of value-added chemicals since it contains molecules that can be used as building blocks. Wood is the preferred input, but still, the production of main outpus (BTEX) are still cheaper in the conventional way.
Lignocellulosic fractions	Pyrolysis	Empyro	Decomposing biomass by heat in the absence of oxygen that produces char, bio-oil, and syngas. Some of the applications of char are fossil fuel, soil amendment and precursor for making

			catalysts and contaminants adsorbents. Bio-oil is a complex mixture of water and organic chemicals with more than 300 identified compounds (such as organic acids sugar and phenols) that can be extracted through bio-refining. Last but not least, the pyrolysis gas contains carbon dioxide, carbon monoxide, methane, hydrogen, ethane, ethylene and might be burned to produce heat.
Food fraction	Production of bioplastics (polihidroxialcanoates, polyethylene furanoates)	Avantium	At the moment, PHAs are being produced on commercial scale on the basis of sugars like food-processing wastes as molasses and whey or starch-containing agricultural or food-processing wastes could also be used after chemical or enzymatic hydrolysis of starch. Monosaccharides for PHA synthesis can be produced from lignocellulosic materials to reduce the cost of raw materials. Promising for waste water treatment plants (Brolsma)
Food fraction/Lignocellulose	Sugar extraction from lignocellulose	*Relevant stakeholder*	Cellulose and hemicellulose can be extracted from lignocellulose with a combination of strong and weak acidic and basic conditions, use of high temperature steam and use of enzymes. Suitable inputs are straw from cereals (wheat and barley), corn starks and sotver, wood chips, grass. The 50-60% of their dry weighs accounts for polysaccharides while vegetable and food waste accounts for the 33%. The outputs of the process consist in a mixture of glucose, xylose and other sugars diluted in an aqueous solution. Plants that produce bio-ethanol from lignocellulose are still not economically profitable and main research efforts focus in reducing the production costs.
Food fraction	Organic fatty acids	Chaincraft	Chain elongation is an interesting process because MCFA can be used as antimicrobials and corrosion inhibitors, as precursors in biodiesel production, bioplastics production and other biobased chemical production processes. A definite strength of the process is that it can be performed in non-sterile enviroments with mixed microbial cultures
Food fraction/Garden waste	Production of bio-aromatics		

Section 1.3. Preliminary conclusions handed to the interviewees

Household level circulation (Composting bins, Composting toilets, Vermicomposting, Low-tech biofilters)
The approach is generally performed by low-tech technologies. Process are simple and occur spontaneously, and thus, they present low energy and water use and low economic costs. Thus, the environmental impact is really low since emissions due to transport are avoided as well as chemicals in pre-treatment of material flows. The variety of possible products is low, but they have the potential of directly restoring the ecosystems (compost, fresh water). An important advantage is that the composition of the inputs does not threat the process because almost the total fraction of material undergoes the transformation and high amount of mas fractions are recovered. Household loop closure implies high social learning and engagement.
Weaknesses of closing the loop at household level exist as well. Firstly, circulation of organic waste at the household level with the current technologies implies health risks and discomfort from the users side, which threatens its acceptability. No coordination of behaviour among citizens is required, but coordinated implementation certainly is, if the environmental benefits are seeked to be materialised. Moreover, implementing this technologies to numerous households consists of a strong top-down approach that could open political discussions. The process are not innovative, they do not stimulate knowledge creation, international cooperation, nor digitalisation or smart logistics. The products are unvaried and with hardly any economic value materials are kept at a household level, they are not accessible to different stakeholders nor market sectors in Amsterdam. Despite some isolated cases, the incidence of such approach is currently low in Amsterdam. They present no potential of employment generation.

Building level circulation (Outdoor composting piles, Worm hotels, Sandy and helyofilters, Struvite precipitation).
The approach leaves room for higher-tech technologies compared to household level. Composting and vermicomposting at higher scales slightly lowers the economic costs per processed amount of material. The environmental impact is still low due to avoidance of emissions due to transport to centralised facilities or maintenance of infrastructure. Nevertheless, higher tech implies complex process that present opportunities for obtaining higher value by-products, such as biofuels from algae cultivation or struvite precipitation. This implies higher innovative processes that can be inspiring to other stakeholders and whose know-how can be exported to other countries. The higher maintenance and rebuilding of facilities against this innovative technologies implies a certain potential for employment generation and the technologies are still close to users so the educational aspect, being a bit lower than at the household scale, is still there.
Weaknesses of the process are still the relatively low variety of by-products obtained that might have relatively low economic value and not be of interest to stakeholders. The costs of adapting the existing facilities to new ones plus de costs of maintenance might be a limiting factor for its expansion. Coordinated behaviour needs to take place (sorting the organic waste, using urine-diverting toilets) in order to get the benefits from its implementation, thus affecting to some extent the lifestyle of the users. De-centralisation from central sanitating systems also increases risks. The amount of by-products recovered might be uninteresting for markets or industries.

Neighbourhood level circulation (Nieuw West GFT management/ Biomeiler, Buurtcompost, Constructed wetlands, Anerobic digestion decentralised plant)
Even though the transforming principles are similar, the larger scale of the processes opens the possibility to harvest not only significant amounts of side by-products (leachate to be used as fertilizer, biogas) but also capture significant amounts of energy (heat from the thermophilic

phase of composting, combustion of the biogas to generate electricity…). In principle, materials should be kept inside the economic system and transforming them to energy is recommended only when further recovery is not possible, since energy can only be looped once while materials are looped indefinitely. Nevertheless, decentralised energy production originates more resilient neighbourhoods less dependent from central facilities. Also, the larger scale leaves room to provision of ecosystems services (the case of constructed wetlands) and since coordinated behaviour is required, societal learning also takes place. Systems are innovative, initial investments might be high but maintenance costs are low in comparison with the volume of material processed. Emissions and costs of transport of waste to central facilities are avoided. Cooperation among local stakeholders takes place and knowledge exchange and possibilities to inspire other municipalities are high.
Still, there is a few certainty on how private businesses could take part on this systems, the range of by-products obtained is still low and are mostly of low economic value.

<u>Larger scale circulation</u> (Bio-refinery approaches, combustion approaches, centralised waste water treatment, large scale anaerobic processes).
Large scale and centralised processes are characterised by being high tech processes. A direct observation lays on the fact that the variety of processes is large, as well as the range of by-products that can be possibly obtained. Thus, their environmental impact is not favourable since it requires the transportation of the materials to the facilities (emissions) and processes usually require pre-processing phases with the use of physical process or the addition of chemicals that embed high environmental impacts. The composition of the streams need to be highly controlled so that the process can take place and be economically profitable. The process usually recovers a relatively small fraction (in mass terms) of the total mass from the waste stream. Moreover, the safety of the streams need to be certified when any of the by-products is to be used for human consumption, which makes the use of household organic waste (highly uncertain composition) not possible for the moment. The societal benefits such as education or engagement are lost due to the disconnection from the citizens to the technologies. The main large-scale technologies (keeping central sanitation systems apart) are still under development and present a bit of high uncertainty.
Nevertheless, the products and by-products obtained are of high economic value, high interest for local stakeholders and these complex processes are innovative, contribute to knowledge generation, international cooperation and digitalisation if reverse logistic strategies are implemented. Moreover, the processes not only provide building blocks that prevent its extraction from fossil fuels, but also provide important amounts of energy and drinkable water that are used locally, which also increases the resilience of the metropolitan area. The cooperation among local industries leads to win-win situations and interactions based on industrial symbiosis that generate knowledge and stimulate innovative business models.

Table 1.4. List of interviewed experts

Name	Institution	Profile	Field of expertise
Jeroen Sluijsmans	WUR	Academic	Nutrient Recovery
Miriam van Eekert	WUR	Academic	Environmental technology
Otto Reinstra	Waternet	Practitioner	Waste water treatment
Coert Petri	Waterboard Rijn en Ijssel	Practitioner	Waste water treatment
Bert Annevelink	WUR	Academic	Biomass value chains

Section 1.5. Item list for the interviewees

- Value recovery from household organic waste: Cases, experiences (in Amsterdam)
- Trends in centralisation/decentralisation of sanitation infrastructure
- Development of high-tech small-scale infrastructure
- Suitability of household waste to be used as an input for high-tech solutions
- Sustainability of bio-processes
- Feedback and ranking criteria (completeness, redundancy, operationality).
- Feedback on inventory technologies (relevance, representative)
- Relevance of Circular Economy in the water sector in the Netherlands.
- Scales of de-centralised waste water management
- Organic nutrients' recovery from waste water streams
- Valorisation opportunities for organic waste in water streams

Appendix 2: Criteria and indicators

Table 2.1. Technology sustainability assessment (Dewulf & Van Langenhove, 2005)

Criteria	Indicator
Conversion concerns: efficiency item	$\eta = \frac{R_{\mathrm{P}}}{R_{\mathrm{Extr}} + R_{\mathrm{Re\text{-}used}}}$
Industrial ecology concern: re-use of materials	$\rho = \frac{R_{\mathrm{Re\text{-}used}}}{R_{\mathrm{Extr}} + R_{\mathrm{Re\text{-}used}}}$
Industrial ecology concern: recovered waste materials item	$\sigma = \frac{R_{\mathrm{Recov}}}{R_{\mathrm{P}}}$
Environmental concerns: renewability item	$\alpha = \frac{R_{\mathrm{Prod}}}{R_{\mathrm{Extr}}}$
Environmental concern: toxicity of emissions item	$t = \frac{R_{\mathrm{Det}}}{R_{\mathrm{Em}}} \frac{R_{\mathrm{Em}}}{R_{\mathrm{P}}} = \frac{R_{\mathrm{Det}}}{R_{\mathrm{P}}}$

Table 2.2. Urban Harvest Approach framework of indicators (Leusbrock et al., 2015)

Criteria	Indicator
Demand minimization index (DMI)	$\mathrm{DMI} = \frac{\text{Baseline demand} - \text{Minimized demand}}{\text{Baseline demand}}$
Waste output index (WOI)	$\mathrm{WOI} = -\frac{\text{Exported waste}}{\text{Minimized demand}}$

Self-sufficiency index (SSI)	$$SSI = \frac{\text{Harvested resources (Rh)} - \text{exported resources}}{\text{Minimized demand}}$$
Resource export index (RXI)	$$RXI = \frac{\text{Exported resources}}{\text{Minimized demand}}$$

Table 2.3. Urban metabolic profiles (Rosado et al., 2016)

MFA indicators to describe urban metabolism characteristics.

Characteristics \ *MFA indicators*	*DMC*	*NAS*	*DMI*	*IMP*	*DE*	*IP*	*EXP*	*DPO*	*Recovery*	*Combination*
1,1 Total Needs			■							
1,2 Final consumption needs	■									
2. Accumulation		■								
3. Efficiency	■								■	Recovery/DMC
4. Diversity of Processes					■	■				DE + IP
5. Support exogenous systems							■			
6. Dependency			■							IMP/DMI
6,1 Dependency from ROW			■	■						iIMP/DMI
6.2 Dependency from ROC			■	■						nIMP/DMI
7. Self-sufficiency	■	■			■					DMC-DE-NAS
8,1 Outputs to nature								■		
8,2 Depletion			■							non renewable DMI/DMI

Table 2.4. Characteristics of a CE full list

Characteristics of a Circular Economy	EMF	EEA	NL	AMS
Renewable energy sources	x	x	x	x
Design for re-use (disassembly, refurbishment…)	x	x		x
Design for resilience (modularity, versatility, adaptability…)	x	x		x
Composting of biological nutrients	x			
High-quality use of biomass waste (cascading)	x	x	x	x
Societal engagement			x	x
Cooperation among production chains' actors	x		x	x
Reducing the extraction of raw materials				
Reducing the amount of imported raw materials		x	x	
Reducing GHG emissions along the product's life cycle				
Reducing water and energy use in production	x	x		
Sustainable sourcing of raw materials		x	x	
Avoiding incineration or landfill by keeping materials inside the loop	x	x	x	x
Extending products' life	x	x		
High-quality recycling of technological nutrients	x	x		x
Replacing fossil fuels by sustainably produced biomass	x		x	x
Cooperation: exportation of knowledge and expertise			x	
Local/regional approach			x	x
Increasing efficiency through digitalisation			x	
Generation of economic value			x	x
Innovative business models			x	x

Innovative technological processes			x	x
Positive contribution to ecosystems				x
Employment generation		x	x	x

Appendix 3. Performance matrix

Table 3.1 Scoring table

		1	2	3	4	5
Energy and water use	Net consumption of energy during the process	Large energy consumption	Moderate to large energy consumption	Moderate energy consumption	Moderate to low energy consumption	No energy consumption
	Net consumption of fresh water during the process	Large fresh water consumption	Moderate to large fresh water consumption	Moderate fresh water consumption	Moderate to low fresh water consumption	No fresh water consumption
	Net consumption of chemical use during the process	Large chemical consumption	Moderate to larghe chemical consumption	Moderate chemical consumption	Moderate to low chemical	No chemical consumption
Environmental impact	Impact of (by-)products to environmental pressures	Cause additional large environmental pressures	Cause additional moderate environmental pressures	No relation to environmental pressures	Indirectly helps improving environmental pressures	Largely helps improving environmental pressures
	Fossil fuel replacement of (by-)product(s)	No fossil fuel replacement	Moderate fossil fuel replacement in energy terms	High fossil fuel replacement in energy terms	Moderate fossil fuel replacement in material terms	High fossil fuel replacement in material terms
	GHGs transport emissions	Large additional emissions	Moderate to large additional emmission	Moderate additional emmissions	Very few additional emissions	No additional emissions
Closed loops	Material fraction recovery and cascading potential	No material fraction recovery	The material fraction recovered is low and the rest cannot be cascaded	The material fraction recovered is low but the rest can be cascaded	The material fraction recovered is high	Almost all mass fraction is recovered

	The process removes material from material cycles due to combustion	Almost all material is lost in combustion	Most of the material is lost in combustion	A moderate material fraction is lost in combustion	Most of the material is kept after combustion	No combustion involved
Innovation	The process is innovative	Incremental innovation		Disruptive innovation		Radical innovation
	Improvement of the sustainability of other business models	Very low potential	Low to moderate potential	Moderate potential	Moderate to high potential	High potential
Local benefits	Expertise about the process is found in Amsterdam	There is no expertise in Amsterdam	There is low to moderate expertise in Amsterdam	There is moderate expertise in Amsterdam	There is moderate to high expertise in Amsterdam	There is high expertise in Amsterdam
	The consolidation of this process could make of Amsterdam an inspiration for other municipalities	Very low potential	Low to moderate potential	Moderate potential	Moderate to high potential	High potential
Cooperation	Interest of (by-)product(s) to local industrial stakeholders	There exist no local market	The local market is very reduced	There exist local market opportunities	The local market opportunities are moderately high	The local market opportunities are high
	World impact, international cooperation, knowledge exchange	Very low potential	Low to moderate potential	Moderate potential	Moderate to high potential	High potential
Economy	Potential exportation of (by-)product(s) to other countries	Very low exportation potential	Moderate to low exportation potential	Moderate exportation potential	Moderate to high exportation potential	High exportation potential

	Economic value of the (by-)product(s)	The (by-)product(s) have no economic value	The (by-)product(s) have a moderate-low economic value	The (by-)product(s) are moderately valuable	The (by-)product(s) have a moderate-high value	The (by-)product(s) have a moderate-high economic value
	Economical sustainability	The process will be economically sustainable in the long term	The process will be economically sustainable in the short term	The process is economically sustainable	The process is economically sustainable and moderately profitable	The process is economically sustainable and highly profitable
	Digitalisation and traceability of the local economy	The process remains untraceable	The process is very difficult to trace	The process can be traceable	The process is moderately easy to trace	The process is very easy to trace
Resilience	Demand of the process for local raw materials	The process largely increases the demand for local raw materials	The process moderately increases a demand for local raw materials	The process does not relate to local raw materials	The process moderately reduces the demand for local raw materials	The process largely reduces the demand for local raw materials
	Demand of the process for imported materials	The process largely requires imported materials	The process moderately requires imported materials	The process does not relate to imported materials	The process eliminates a moderate need for imported materials	The process largely replaces imported materials
Society	Societal learning and engagement	The process remains unknown by the society	Only a few sectors of society might know about the process	The process would be well known	The process would be well known and adopted by some sectors of the society	The process would be well known and adopted by all sectors of the society
	Risks for public health	High risks for public health	Moderate risks for public health	No risks for public health	Moderate reduction of	High reduction of public health risks

					public health risks	
	Change in the habits of society	Large discomfortable changes	Moderate discomfortable changes	No changes	Moderate comfortable changes	Large comfortable changes

Table 3.2 Overview of the performance matrix

MICRO						MESO					MACRO														
ANAER. COMP.	WORMERY	BOKASHI	COMPOSTING TOILETS	BIOFILTERS	STRUVITE	WORM HOTEL	BIOMEILER	NIEUW WEST	WETLAND	BUIKS	W2A	MCFA	ETHANOL	GASIFICATION	PYROLISIS	TRANSESTERIFICATION	ORGAWORLD	PHA	BSF	WATERNET	P-t-P	EFGF	SANIPHOS	LANDFILL	AEB
5	5	5	5	5	5	5	5	5	5	5	2	2	2	4	4	2	4	1	2	2	2	2	3	5	2
5	5	5	5	5	5	4	4	4	5	4	2	2	3	4	3	4	3	1	3	3	5	4	5	4	5
5	5	5	5	5	3	5	5	5	5	4	2	2	2	2	4	2	3	1	3	2	3	4	3	5	2
4	4	4	3	4	4	4	4	4	4	3	2	3	2	1	2	2	4	2	4	5	4	4	4	1	3
1	1	1	3	1	4	1	3	1	1	3	5	5	3	4	4	5	3	5	1	2	1	4	4	1	4
5	5	5	5	5	5	5	4	2	5	4	2	3	2	5	2	3	4	2	2	4	2	4	2	1	2
4	4	4	5	5	4	4	5	5	5	5	5	5	4	4	4	4	4	2	4	5	5	5	5	1	5
5	5	5	4	3	5	5	5	5	5	4	4	5	4	4	3	5	4	5	5	5	5	5	5	5	5
1	2	2	3	1	4	3	3	2	4	4	5	5	4	4	5	4	5	5	3	4	5	5	5	1	3
1	1	1	3	1	3	2	2	4	3	4	4	5	4	4	4	5	4	5	4	3	4	4	4	1	3
2	2	2	3	2	4	2	2	3	4	4	5	5	4	4	4	5	5	4	4	4	4	5	4	1	5
2	2	2	3	4	4	2	4	3	5	4	4	3	3	3	3	3	3	2	3	2	4	3	4	1	2
1	1	1	1	5	3	1	1	3	3	4	4	4	4	3	4	4	2	3	5	2	4	2	4	1	2
2	2	2	3	1	3	2	3	3	1	4	5	5	5	5	5	5	4	4	5	3	4	3	5	1	3
3	3	3	3	5	3	3	4	4	4	3	1	4	4	4	5	5	4	2	5	3	2	4	4	4	5
1	1	1	3	1	3	4	3	5	5	5	5	5	2	3	5	5	5	5	5	5	4	4	4	5	5
3	3	3	3	3	4	3	3	4	3	4	5	4	2	3	4	5	4	4	4	3	4	3	4	3	4
5	5	5	3	5	5	5	4	5	3	3	1	1	1	1	1	1	1	1	1	1	2	2	4	1	1
4	4	4	2	4	3	4	4	4	5	4	5	5	5	5	5	5	5	5	4	5	5	5	3	2	5
2	2	2	4	3	3	2	3	2	5	2	5	5	5	5	1	5	5	5	5	5	2	5	2	5	5